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UNPRECEDENTED COSMIC COLLISIONS DETECTED BY LIGO
BLACK HOLES
The extreme science of the universe's most mysterious phenomena
WHAT'S AT THE CENTER OF THE MILKY WAY?
NEUTRON STAR SHREDDERS

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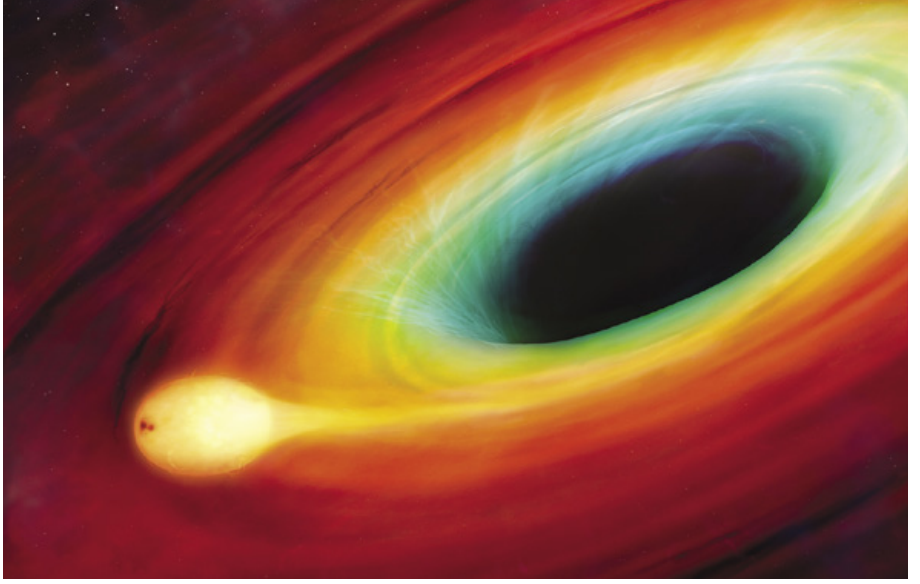


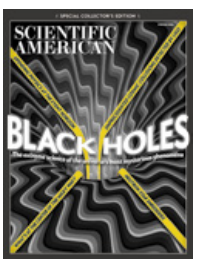
MARK GARLICK *Alamy*

FROM THE EDITOR

Golden Age of Black Holes

The past five years have brought a spate of astounding black hole observations: the first detection in 2015 of gravitational waves from the collision of two black holes; an unprecedented x-ray look in 2018 at a dozen black holes spinning around the supermassive black hole at the center of the Milky Way; and the first-ever photo of a black hole (at the center of the Messier 87 galaxy) in 2019. Nearly 100 years after Albert Einstein predicted their existence, the direct confirmations are rolling in and revolutionizing astrophysics.

The mere existence of black holes had been an open question, even until the 1990s (*page 8*)—how the oldest and biggest ones could possibly have formed so soon after the big bang was particularly vexing (*page 14*). An unshakable belief that a monster supermassive black hole lurked at the center of our own galaxy was only vindicated after more than a decade of work by Nobel-winning physicists Andrea Ghez, Reinhard Genzel, and others (*page 12*).



Cover illustration by Yurii Perepadia

Black holes exert a strong influence across the cosmos. Their immense gravitation creates the shapes of galaxies, and perhaps black holes themselves are the invisible dark energy in the universe (*page 26*). While locking in a swarm of clouds of dust around their cores (*page 32*), they feed on neutron stars (*page 36*) and other luminary bodies that succumb to their pull (*page 40*).

The quandary of black holes is that they upend the very laws of classical physics that foretold their existence (*page 48*). At the event horizon, the boundary of a black hole, quantum physics breaks down (*page 70*), and quantum information is destroyed entirely or perhaps propelled from one coordinate in the universe to another via a wormhole connecting two black holes (*page 64*).

Sophisticated new technologies have brought us from theory and oblique measurements to direct evidence of black holes. That first image of the supermassive black hole in 2019 (*page 78*) has been joined by observations of the light from merging black holes (*page 84*) and of as yet uncategorized objects that might be black holes, neutron stars, or something else (*page 88*).

No new technology is ushering in the golden age of black holes faster than the gravitational-wave detectors. Their influence ripples through nearly every story in this collection, from the riveting tale of their first observations (*page 96*) to their sensing of new classes of black holes (*page 104*) and the so-called galactic factories that generate them (*page 108*).

Astrophysicists today have tremendous instruments and databases that give them an unprecedented look into the dark. But much remains unseen. Black holes are ubiquitous throughout the cosmos, yet they persist in shadow, leaving humanity to guess at and test their meaning, both from behind the telescope and in our imagination.

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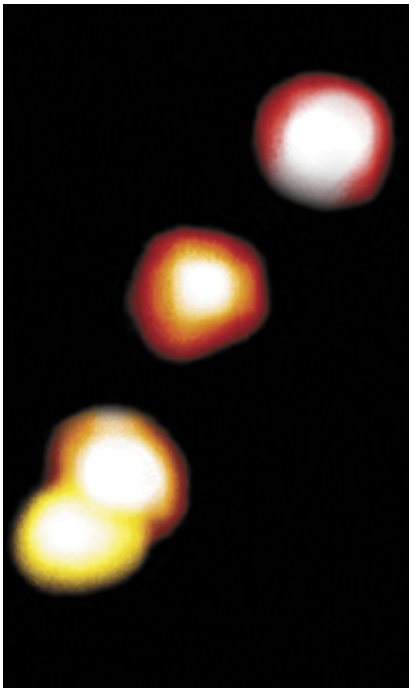

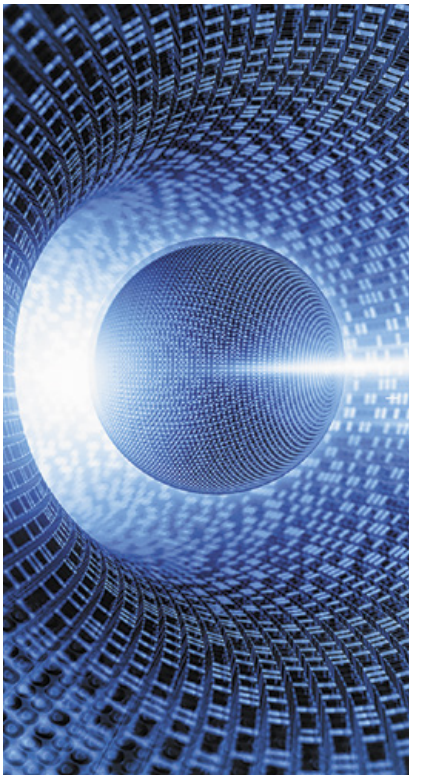

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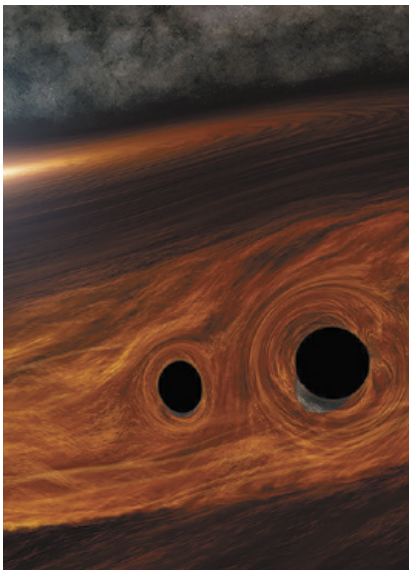

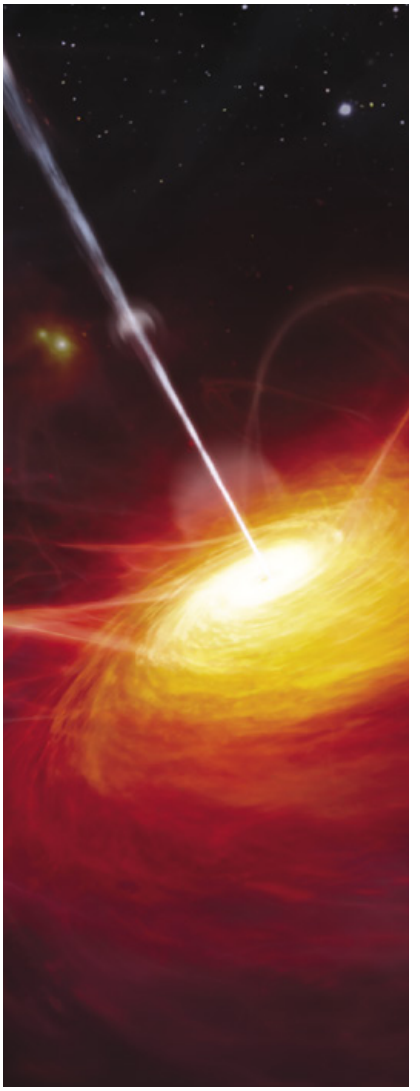

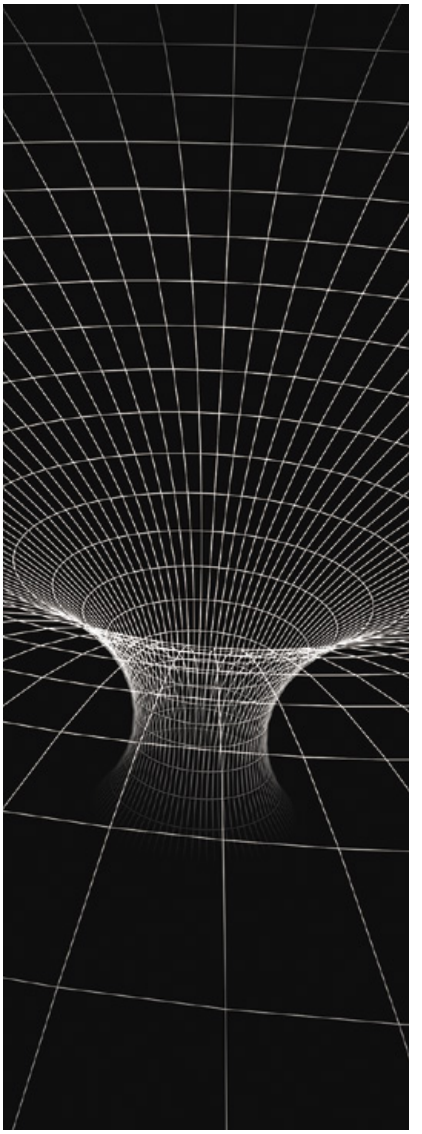

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HEAD TRIP

Einstein's thought experiments left a long and somewhat mixed legacy of their own

By Sabine Hossenfelder

GEDANKENEXPERIMENT, GERMAN FOR "THOUGHT EXPERIMENT," WAS Albert Einstein's famous name for the imaginings that led to his greatest breakthroughs in physics. He traced his realization of light's finite speed—the core idea of special relativity—to his teenage daydreams about riding beams of light. General relativity, his monumental theory of gravitation, has its origins in his musings about going up and down in an elevator. In both cases, Einstein crafted new theories about the natural world by using his mind's eye to push beyond the limitations of laboratory measurements.

Einstein was neither the first nor the last theorist to do this, but his remarkable achievements were pivotal in establishing the *Gedankenexperiment* as a cornerstone of modern theoretical physics. Today physicists regularly use thought experiments to craft new theories and to seek out inconsistencies or novel effects within existing ones.

But the modern embrace of thought experiments raises some uncomfortable questions. In the search for a grand unified theory that would wed the small-scale world of quantum mechanics with Einstein's relativistic description of the universe at large, the most popular current ideas are bereft of observational support from actual experiments. Can thought alone sustain them? How far can we trust logical deduction? Where is the line between scientific intuition and fantasy? Ein-

Illustration by Sam Falconer

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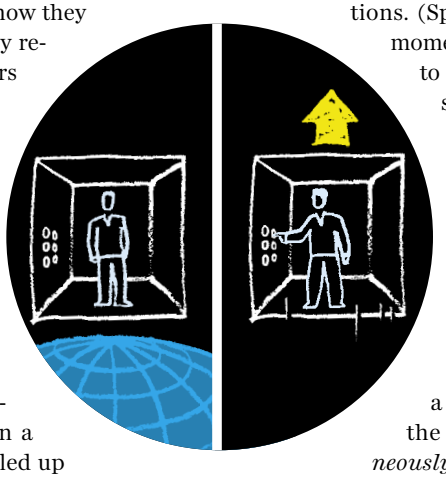
stein's legacy offers no certain answers: On one hand, his reliance on the power of thought was a spectacular success. On the other, many of his best-known thought experiments were based on data from real experimentation, such as the classic Michelson-Morley experiment that first measured the constancy of the speed of light. Moreover, Einstein's fixation on that which can be measured at times blinded him to deeper layers of reality—although even his mistakes in thought experiments contributed to later breakthroughs.

Here we will walk through some of Einstein's most iconic thought experiments, highlighting how they succeeded, where they failed and how they remain vital to questions now at the frontiers of theoretical physics.



THE WINDOWLESS ELEVATOR

IN HIS THOUGHT EXPERIMENTS, Einstein's genius was in realizing which aspects of experience were essential and which could be discarded. Consider his most famous one: the elevator thought experiment, which he began devising in 1907. Einstein argued that inside a windowless elevator, a person cannot tell whether the elevator is at rest in a gravitational field or is instead being hauled up with constant acceleration. He then conjectured that the laws of physics themselves must be identical in both situations. According to this "principle of equivalence," locally (in the elevator), the effects of gravitation are the same as those of acceleration in the absence of gravity. Converted into mathematical equations, this principle became the basis for general relativity. In other words, the elevator thought experiment motivated Einstein to make the daring intellectual leap that ultimately led to his greatest achievement, his geometric description of gravity.

SPOOKY ACTION

LATER IN HIS CAREER, Einstein fought hard against the tenets of quantum mechanics, particularly the uncertainty principle, which dictates that the more you know about one aspect of a fundamental particle, such as its position, the less you can know about a different, related aspect of that particle, such as its momentum—and vice versa. Einstein thought that the uncertainty principle was a sign that quantum theory was deeply flawed.

During a years-long exchange with Danish quantum theorist Niels Bohr, Einstein conceived of a series of thought experiments meant to demonstrate that it is possible to violate the uncertainty principle, but Bohr dissected every one of them. This exchange bolstered Bohr's conviction that quantum uncertainty was a fundamental aspect of nature. If not even the great Einstein could devise a way to precisely measure both the position and the momentum of a particle, then certainly there must be something to the uncertainty principle!

In 1935, along with his colleagues Boris Podolsky and Nathan Rosen, Einstein published what was meant to be his most potent critique of the uncertainty principle. Perhaps because Podolsky, not Einstein, drafted the actual text of the paper, this Einstein-Podolsky-Rosen (EPR) thought experiment was presented not as an easy-to-imagine scenario of boxes, clocks and light beams but as an abstract series of equations describing interactions between two generalized quantum systems.

The simplest version of the EPR experiment studies the paradoxical behavior of "entangled" particles—pairs of particles that share a common quantum state. It unfolds as follows: imagine an unstable particle with a spin of zero decaying into two daughter particles, which speed off in opposite directions. (Spin is a measure of a particle's angular momentum, but counterintuitively, it has little to do with a particle's rate of rotation.) Conservation laws dictate that the spins of those two daughter particles must add up to zero; one particle, then, could possess a spin value of "up," and the other could have a spin value of "down." The laws of quantum mechanics dictate that in the absence of measurement, neither of the particles possesses a definite spin until one of the two speeding entangled particles is measured. Once a measurement of one particle is made, the state of the other changes *instantaneously,* even if the particles are separated by a vast distance!

Einstein believed this "spooky action at a distance" was nonsense. His own special theory of relativity held that nothing could travel faster than light, so there was no way for two particles to communicate with each other instantaneously from opposite sides of the universe. He suggested instead that the measurement outcomes must be determined prior to measurement by "hidden variables" that quantum mechanics failed to account for. Decades of discussion followed until 1964, when physicist John Bell developed a theorem quantifying exactly how the information shared between entangled particles differs from the information that Einstein postulated would be shared through hidden variables.

Since the 1970s lab experiments with entangled quantum systems have repeatedly confirmed that Einstein was wrong, that quantum particles indeed share mutual information that cannot be accounted for by hidden variables. Spooky action at a distance is real, but experiments have demonstrated that it cannot be used to transmit information faster than light, making it perfectly consistent with Einstein's special relativity. This counterintuitive truth remains one of the most mysterious conundrums in all of physics, and it was Einstein's stubborn, mistaken opposition that proved crucial to confirming it.

ALICE AND BOB

TODAY SOME OF THE MOST SIGNIFICANT thought experiments in physics explore how to reconcile Einstein's clockwork, relativistic universe with the fuzzy uncertainties inherent to quantum particles.

Consider, for instance, the widely discussed black hole information paradox. If you combine general relativity and quantum field theory, then you find that black holes evaporate, slowly radiating away their mass because of quantum effects.

Illustrations by Nigel Holmes

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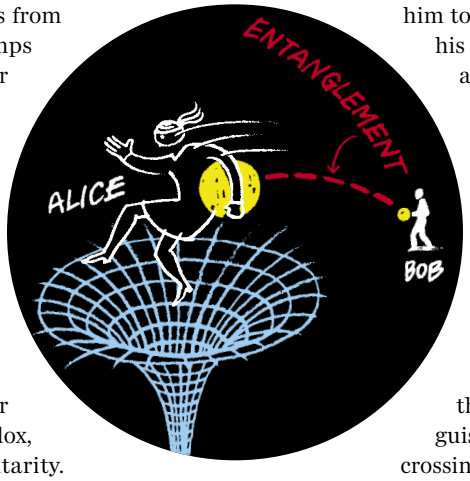
You also find that this process is not reversible: regardless of what formed the black hole, the evaporating black hole always produces the same featureless bath of radiation from which no information about its contents can be retrieved. But such a process is prohibited in quantum theory, which states that any occurrence can, in principle, be reversed in time. For instance, according to the laws of quantum mechanics, the leftovers of a burned book still contain all the information necessary to reassemble that book even though this information is not easily accessible. Not so for evaporating black holes. And so we arrive at a paradox, a logical inconsistency. A union of quantum mechanics and general relativity tells us that black holes must evaporate, but we conclude that the result is incompatible with quantum mechanics. We must be making some mistake—but where?

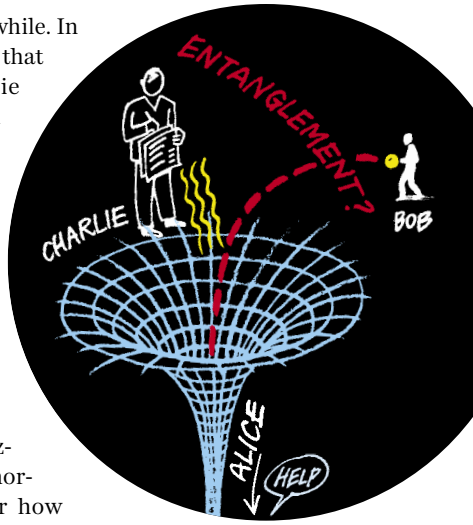
The thought experiments created to explore this paradox typically ask us to imagine a pair of observers, Bob and Alice, who share a pair of entangled particles—those spooky entities from the EPR experiment. Alice jumps into the black hole, carrying her particle with her, whereas Bob stays outside and far away with his. Without Alice, Bob's particle is just typical, with a spin that might measure up or down—the information that it once shared with its entangled partner is lost, along with Alice.



Bob and Alice play a central role in one of the most popular proposed solutions to the paradox, called black hole complementarity. Proposed in 1993 by Leonard Susskind, Lárus Thorlacius and John Uglum, all then at Stanford University, black hole complementarity rests on Einstein's golden rule for a *Gedankenexperiment:* a strict focus on that which can be measured. Susskind and his colleagues postulated that the information falling in with Alice must come out later with the evaporating black hole's radiation. This scenario would usually create another inconsistency because quantum mechanics allows only pair-wise entanglement with one partner at a time, a property called monogamy of entanglement. That is, if Bob's particle is entangled with Alice's, it cannot be entangled with anything else. But black hole complementarity requires that Bob's particle be entangled with Alice's *and* with the radiation the black hole later emits even though this violates monogamy. At first sight, then, black hole complementarity seems to exchange one inconsistency for another.

But like a perfect crime, if no one actually *witnesses* this inconsistency, perhaps it can subvert nature's otherwise strict laws. Black hole complementarity relies on the argument that it is physically impossible for any observer to see Alice and Bob's entangled particles breaking the rules.

To envision how this perfect quantum-mechanical crime could unfold, imagine a third observer, Charlie, hovering near the black hole, keeping an eye on Alice and Bob. He watches as Bob stays outside and as Alice falls in, measuring the black hole's emitted radiation all the while. In theory, information encoded in that radiation could tip off Charlie that Bob and Alice had violated the monogamy of their entanglement. To know for certain, however, Charlie would have to compare his observations not only with Bob's measurement but also with Alice's—inside the black hole. So he must hover at the horizon, measure the emitted radiation, then jump in to tell Alice what he has found. Amazingly enough, Susskind and Thorlacius showed that no matter how hard Charlie tries, it is impossible for him to enter the black hole and compare his information with Alice's before they are both torn apart by tidal forces. Their grisly fate suggests no violations of quantum mechanics can ever be measured by anybody around a black hole, and so theorists can commit this crime against nature with impunity.



Suffice it to say, not all theorists are convinced that this argument is valid. One criticism of black hole complementarity is that it might violate Einstein's equivalence principle—the one that grew out of his elevator thought experiment. Einstein's general relativity predicts that just as the elevator's passenger cannot distinguish between gravity and acceleration, an observer crossing a black hole's horizon should not notice anything unusual; there is no way an observer can tell that he or she has slipped past the point of no return.

Now let us return to the entanglement of Alice and Bob. If the radiation that Bob sees from far outside the hole contains all the information that we thought vanished with Alice behind the horizon, then this radiation must have been emitted with an extremely high energy; otherwise, it would not have escaped the strong gravitational pull near the horizon. This energy is high enough to vaporize any infalling observer before he or she slips past the black hole's horizon. In other words, black hole complementarity implies that black holes have a "firewall" just outside the horizon—and yet the firewall directly contradicts the predictions of Einstein's equivalence principle.

At this point, we have ventured deep into the realm of theory. Indeed, we might never know the solutions to these puzzles. But because those solutions could lead to an understanding of the quantum nature of space and time, these puzzles are, for better or worse, some of the most vibrant areas of research in theoretical physics. And it all goes back to Einstein's musings about falling elevators. SA

Sabine Hossenfelder is a theoretical physicist at the Frankfurt Institute for Advanced Studies in Germany who researches physics beyond the Standard Model. She is author of the physics blog Backreaction and the book *Lost in Math: How Beauty Leads Physics Astray* (Basic Books, 2018).

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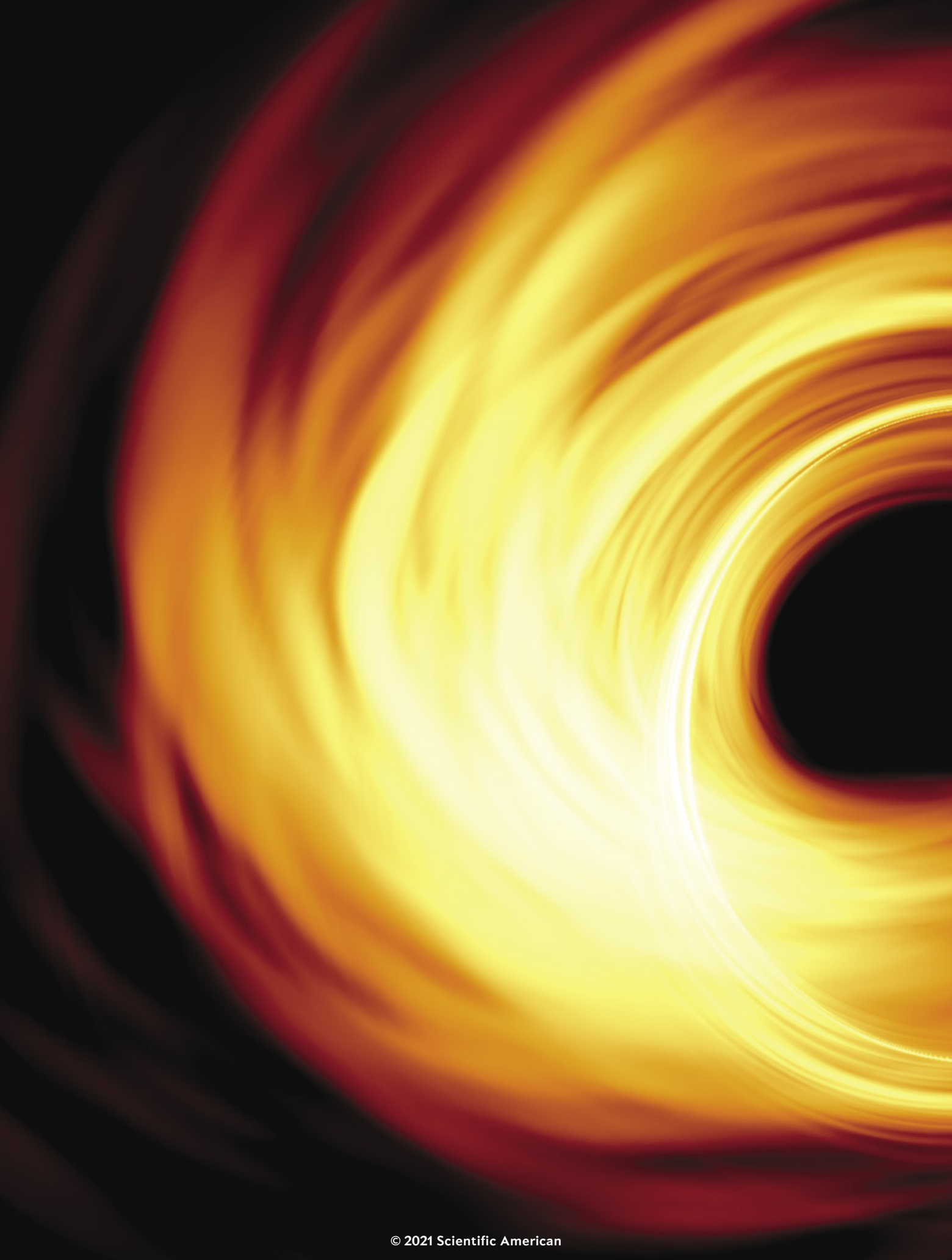

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From Fantasy to Fact

Over the past century the existence of black holes has become unmistakable

By Daniel Garisto

IMAGE from a numerical simulation of an accretion disk around a black hole. The central dark region is the black hole's "shadow."

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AS THE CARNAGE OF THE EASTERN FRONT RAGED AROUND HIM, A GERMAN lieutenant in World War I digested Albert Einstein's new theory. Less than two months after Einstein published his general theory of relativity, Karl Schwarzschild, who had enlisted despite being older than 40 and a physicist, found a way to use it to describe the spacetime of a spherical, nonrotating mass such as a stationary star or planet. Hidden inside Schwarzschild's work was an implication that hinted at the ultimate warpers of spacetime: black holes. He was just 42 when he died months later, in May 1916. But the quest Schwarzschild started has continued for a century, eventually leading to 2020's Nobel Prize in Physics.

The prize was awarded to mathematical physicist Roger Penrose for his "discovery that black hole formation is a robust prediction of the general theory of relativity" and to astrophysicists Andrea Ghez and Reinhard Genzel "for the discovery of a supermassive compact object at the center of our galaxy." It was the first Nobel given specifically for black holes—an acknowledgment of their unmistakable existence (notwithstanding the hedging in the language of the second half of the award). "Nowadays we take these things for granted," says Leo Stein, a physicist at the University of Mississippi. "We've come so far that, at least within our astrophysical community, we think, 'Of course there are black holes.'"

But it was not always so. For decades the concept of black holes was no more than a mathematical aberration. In the years following 1916, Schwarzschild's solution caused interest and some consternation among mathematicians and physicists. His work predicted a "Schwarzschild radius"—a radius that denotes how compact an object would need to be to prevent light from escaping its gravitational pull. The sun, for example, has a real radius of nearly 700,000 kilometers, but its Schwarzschild radius is only three kilometers.

Spacetime curves by an amount relative to an object's Schwarzschild radius divided by its actual radius. The closer the two values are, the more spacetime bends. So what happens when the object's radius is equal to its Schwarzschild radius? And what happens if an object's radius is zero? The answers to those questions were known as singularities—undefined solutions equivalent to dividing by zero on a calculator. At a singularity, spacetime seems to bend to a breaking point.

In the next few decades physicists made some progress, but the search was mostly a mathematical diversion with no ties to the real world. The exotic—and, at the time, entirely theoretical—objects suggested by Schwarzschild's work could be as heavy as the sun but smaller than Central Park or, stranger yet, contain a star's mass within a radius of zero. "People thought, 'Okay, this is just fanciful. We're completely outside the realm of where our physical theory should apply,'" says Frans Pretorius, a physicist at Princeton University.

MONSTROUS MATH

IN THE 1960S Schwarzschild's solutions started to seem more relevant. Astronomers began to observe extreme phenomena, such as distant galaxies spewing jets of particles at energies and amounts impossible for a normal star (dubbed "quasars"—short for "quasi-stellar objects"—these energetic eruptions were eventually traced to feasting supermassive black holes). At the same time, theorists began to model the dynamics of ultracompact cosmic bodies, finding clever ways to avoid the pitfalls associated with singularities. Penrose, then a young mathematician with a keen interest in astrophysics, was in an optimal position to help scientists stymied by the math.

"[Physicists] would argue. They would get answers that didn't agree with each other," says Daniel Kennefick, an astrophysicist and historian of science at the University of Arkansas. "It turned out the reason was that they didn't really understand the structure of infinity, and Penrose solved that problem."

To deal with the complexities of general relativity where spacetime curved in the extreme, as with objects the same size as their Schwarzschild radius, Penrose came up with a set of mathematical tools. In particular, he introduced the mathematical notion of "trapped surfaces" that allowed physicists to confidently pinpoint an event horizon—the point at which even light can never escape the inexorable tug of gravity. (The

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event horizon of a nonrotating black hole is located at its Schwarzschild radius.) Event horizons helped deal with the trickiness of singularities by putting an inescapable barrier around them. "We really don't like having singularities," Stein says. "In fact, we could cut out the inside of the black hole spacetime and replace it with … pink elephants or what have you. And from the outside, you would never be able to tell the difference, because it's all hidden behind the horizon." Penrose's idea of "cosmic censorship" was that there could be no "naked" singularities: all of them would have to be "clothed" by an event horizon. Even when black holes crashed together and merged, the singularities—or pink elephants—would remain hidden by their event horizons, preventing their existence from throwing the outer cosmos into chaos.

A fascination with geometry and artists such as M. C. Escher also led Penrose to develop powerful, intuitive diagrams that captured dynamics of spacetime that were previously out of reach. His diagrams compacted space and time, placing infinities on the page instead of having them stretch off into the distance. "Once it's on the page, you can study it," Kennefick says. "Penrose was a toolmaker par excellence. He invented many of the tools that were used in that period to understand black holes and that we still use today." By the end of the 1960s the term "black hole" had become the accepted nomenclature to describe these hypothetical—but now much less improbable—consequences of general relativity.

ASTROPHYSICAL JUMP SCARE

IT IS HARD to pinpoint exactly when a majority of physicists became believers, but by the mid-1990s black holes were taken for granted even without direct observations of them. Some of the most concrete evidence would come from Ghez's and Genzel's separate work on Sagittarius A*, the then suspected supermassive black hole at the center of the Milky Way. "Often when we're interpreting astronomical observations, there's some wiggle room for some other possibilities," says Suvi Gezari, an astronomer at the University of Maryland, College Park. "What's so beautiful about our galactic center is that the measurements don't allow for any other possibility than a four-million-solar-mass black hole."

To arrive at that level of precision, Ghez and Genzel each independently led teams that spent more than a decade following the path of S02, a star with a short elliptical orbit around Sagittarius A*. In the 16 years it took for S02 to orbit the galactic center, the researchers dramatically improved their telescopes' measurements with a technology called adaptive optics, which uses lasers to correct for blurriness caused when light travels through Earth's atmosphere.

By the time S02 made a complete orbit around a dark patch of nothing, the existence of black holes could not have been clearer. Since then, astronomers have made other direct observations of black holes.

In 2012 Gezari led a team that observed, with unprecedented detail, a tidal disruption event—a tame name for a black hole ripping apart the entrails of a star that got too close. A stellar homicide in another galaxy looks a bit like a brighter, longer supernova, thanks to the rest of the star being flung apart. "I used to call it the 'fingerprints' of the victim—which, in this case, is the star," Gezari says.

More events, such as the merger of two black holes and the ensuing gravitational waves captured by the Laser Interferometer Gravitational-wave Observatory (LIGO) and the Virgo experiment, have given further proof that these objects exist. But perhaps the most stunning evidence thus far is the image taken by the Event Horizon Telescope (EHT) of a supermassive black hole with *billions* of solar masses at the center of the galaxy Messier 87. The now iconic image of a black circle ringed with the intense light of an accretion disk the size of our solar system has eliminated any room for doubt.

"WE COULD CUT OUT THE INSIDE OF THE BLACK HOLE SPACETIME AND REPLACE IT WITH … PINK ELEPHANTS."
—LEO STEIN *UNIVERSITY OF MISSISSIPPI*

These observations of black holes and their shadows are more than just confirmations of Einstein's theory. As the EHT's resolution increases, it will test the very theories that first predicted their existence. "Black hole shadows are a good test in that alternative theories predict something different than what general relativity predicts," says Feryal Özel, an astrophysicist at the University of Arizona and the EHT.

In 2020, by carefully scrutinizing the shape of the shadow seen by the EHT, Özel and her colleagues made some of the most precise measurements of general relativity. So far those measurements agree with predictions, but it is possible that with more precision, deviations from general relativity that hint at a deeper underlying theory will show up.

For astronomers, astrophysicists and mathematicians, black holes are, by turns, monstrous and beautiful; they are extraordinary in their physics but ordinary in their ubiquity. They continue to attract researchers hoping to unlock new secrets of the universe. For a watching public, there is some appeal, too. Evolutionary biologist "Stephen Jay Gould famously wondered, 'Why have dinosaurs become so popular?' and argued that it isn't obvious that they should be," Kennefick says. Black holes, he suggests, have some of the same features as dinosaurs: they seem big, they eat things, and they're a little terrifying—but comfortably far away. SA

Daniel Garisto is a freelance science journalist covering advances in physics and other natural sciences. His writing has appeared in *Nature News*, *Science News*, *Undark*, and elsewhere.

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Unshakable Resolve

How Andrea Ghez won the Nobel for an experiment nobody thought would work

By Hilton Lewis

STANDING IN MY OFFICE 25 YEARS AGO WAS an unknown, newly minted astronomer with a half-smile on her face. She had come with an outrageous request—really a demand—that my team modify our exhaustively tested software to make one of our most important and in-demand scientific instruments do something it had never been designed for and risk breaking it. All to carry out an experiment that was basically a waste of time and couldn't be done—to prove that a massive black hole lurked at the center of our Milky Way.

My initial "no way" (perhaps I used a stronger expression) gradually gave way in the face of her cheerful but unwavering determination. It was my first encounter with a force of nature, Andrea Ghez, one of three winners of the 2020 Nobel Prize in Physics, for her work on providing the conclusive experimental evidence of a supermassive black hole with the mass of four million suns residing at the center of the Milky Way galaxy.

That determination and the willingness to take calculated risks have always characterized Andrea. For 25 years she has focused almost exclusively on Sagittarius A*—the name of our own local supermassive black hole. It is remarkable that an entire field of study has grown up in the intervening quarter century—of searching for and finding evidence of these monsters thought to lie at the heart of every large galaxy. And Andrea is without question one of the great pioneers in this search.

Andrea's co-prizewinner Reinhard Genzel has been involved in the same research from the outset, and it is the work of their two teams—each led by a formidable intellect and using two different observatories in two different hemispheres—that has brought astronomy to this remarkable result: the confirmation of another of the predictions of Einstein's more than century-old theory of general relativity.

As in so many fields of science, the competition has been intense, sometimes brutal, but out of this has been forged an unshakable result that has been tested and retested over a quarter century. And at the heart of the competition are two colleagues, great astronomers each, whose work has been as much defined by the science as by the availability of telescopes and instrumentation almost perfectly suited to this exact scientific endeavor.

Andrea did her work at the W. M. Keck Observatory's twin telescopes on Maunakea, Hawai'i, in the calm and clear air almost 14,000 feet above the Pacific Ocean. She started using the very first instrument commissioned on Keck Observatory's Near Infrared Camera (NIRC), now gracing the lobby at our headquarters. NIRC was never

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GHEZ, one of three winners of the 2020 Nobel Physics Prize, for her work on providing evidence of a supermassive black hole residing at the Milky Way's center.

designed to do what Andrea needed—an ultrafast readout of images and then a restacking of the result to remove the effects of the atmosphere's turbulence. But she was not to be denied—and we made the changes. And it worked! It was supremely hard and time-consuming to make sense of the data, but Andrea persisted.

Out of that effort came the first evidence—not just hints—of stars orbiting the black hole. It was a fantastic result but a long way from full confirmation. Around that time a new technology, adaptive optics (AO), was being installed on telescopes worldwide. Keck Observatory was the first of the most powerful observatories to be so equipped—and the results were electrifying. No surprise: Andrea immediately switched to using AO for her work. She always pushed for more performance and more capability—and the scientists and engineers at Keck Observatory and in our community of instrument builders responded. This push for more and more, and the scientific rewards that followed, is what helped make AO the immensely powerful tool it is today.

Andrea is fond of pointing out that one of the reasons for her success has been this tight and rapid loop between the needs of the astronomers and the engineers who respond to the challenge. In a way reminiscent of the tight synergy between mathematics and physics, science questions beget new technology, and new technology begets new science. Andrea has always been at the forefront of this virtuous cycle, an enthusiastic proponent of "we can do more."

Andrea is a great scientist; not only does she do the science, she molds events to make it possible. In addition to doing research, she has created the UCLA Galactic Center Group to coordinate research and technical developments. And she imbued a cohort of grad students and postdoc fellows with her passion and the thrill of the chase. It is no exaggeration to say that Andrea has personally inspired aspiring scientists everywhere, and she serves as a role model for what ability, grit and commitment can accomplish.

Today Andrea sits at the pinnacle of scientific recognition for her achievements. But as she would be the very first to acknowledge, this triumph represents the combined efforts of so many. From the theoretical predictions of the peerless Albert Einstein, to those who had the vision to build the amazingly complex machines we call simply "telescopes," to the people who created sites at the best locations on Earth for this research, to those who conceive of and build the instrumentation and run the operations, to the science teams that do the research—all of it essential, the product of the work of thousands.

But in the end, one person had the idea for the research. One person had the chutzpah to propose it, and one person had the determination, tenacity and focus to make it happen, undeterred by all who said it was a waste of time. That person is my friend and longtime colleague, the one who refused to take "no" for an answer and who probably doesn't even have it in her vocabulary: Andrea Ghez, winner of the 2020 Nobel Prize in Physics. SA

Hilton Lewis is director of the W. M. Keck Observatory.

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THE FIRST MONSTER BLACK HOLES

Astronomers are puzzled about how the oldest supermassive black holes could have grown so big so early in cosmic history

By Priyamvada Natarajan

Illustration by Mark Ross

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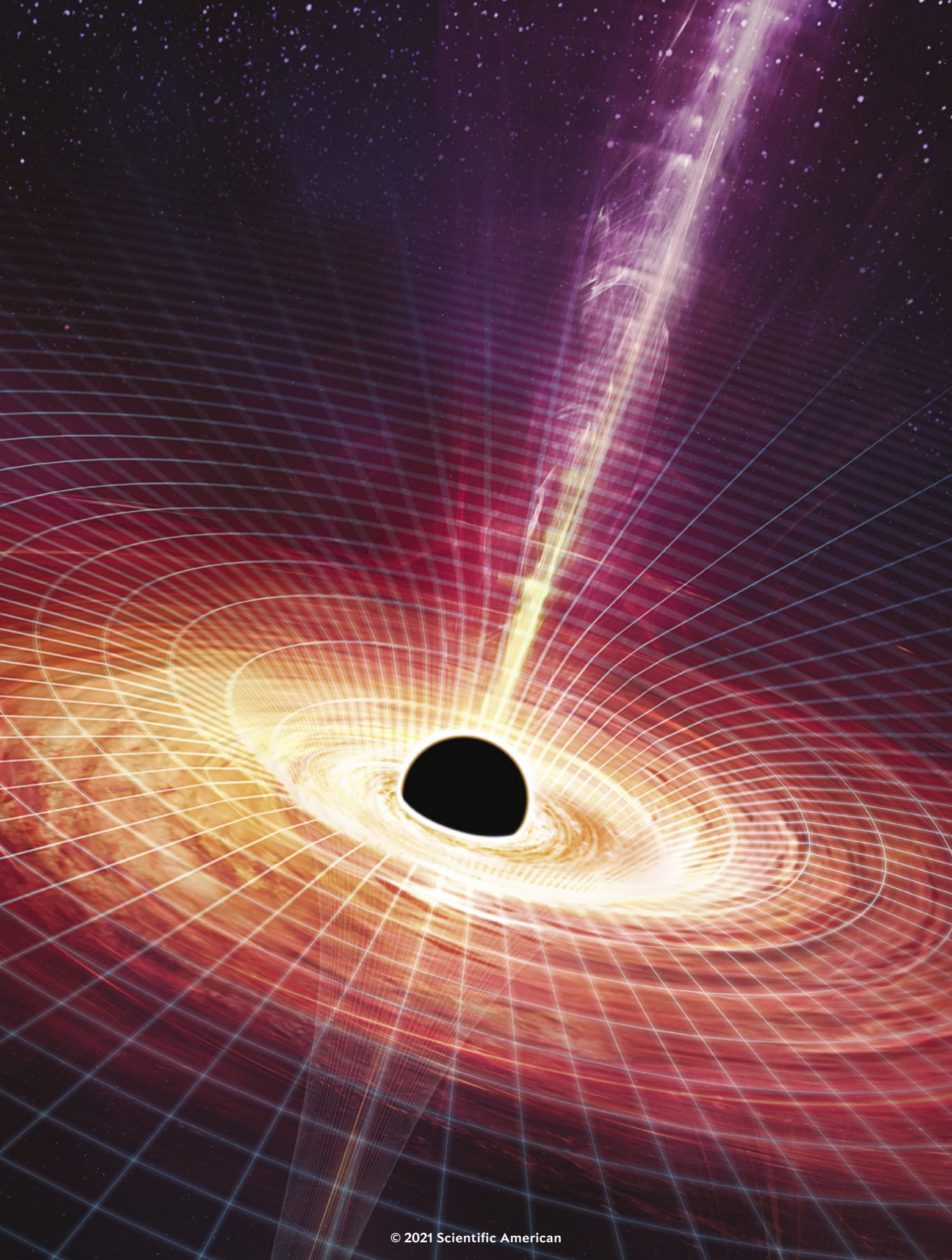

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IMAGINE THE UNIVERSE IN ITS INFANCY. MOST SCIENTISTS THINK SPACE AND TIME originated with the big bang. From that hot and dense start the cosmos expanded and cooled, but it took a while for stars and galaxies to start dotting the sky. It was not until about 380,000 years after the big bang that atoms could hold together and fill the universe with mostly hydrogen gas. When the cosmos was a few hundred million years old, this gas coalesced into the earliest stars, which formed in clusters that clumped together into galaxies, the oldest of which appeared 400 million years after the universe was born. To their surprise, scientists have found that another class of astronomical objects began to appear at this point, too: quasars.

Quasars are extremely bright objects powered by gas falling onto supermassive black holes. They are some of the most luminous things in the universe, visible out to the farthest reaches of space. The most distant quasars are also the most ancient, and the oldest among them pose a mystery.

To be visible at such incredible distances, these quasars must be fueled by black holes containing about a billion times the mass of the sun. Yet conventional theories of black hole formation and growth suggest that a black hole big enough to power these quasars could not have formed in less than a billion years. In 2001, however, with the Sloan Digital Sky Survey, astronomers began finding quasars that dated back earlier. The oldest and most distant quasar known, which was announced in January 2021, existed just 670 million years after the big bang. In other words, it does not seem that there had been enough time in the history of the universe for quasars like this one to form.

Many astronomers think that the first black holes—seed black holes—are the remnants of the first stars, corpses left behind after the stars exploded into supernovae. Yet these stellar remnants should contain no more than a few hundred solar masses. It is difficult to imagine a scenario in which the black holes powering the first quasars grew from seeds this small.

To solve this riddle, more than a decade ago some colleagues and I proposed a way that seed black holes massive enough to explain the first quasars could have formed without the birth and death of stars. Instead these black hole seeds would have formed directly from gas. We call them direct-collapse black holes (DCBHs). In the right environments, direct-collapse black holes could have been born at 10^4 or 10^5 solar masses within a few hundred million years after the big bang. With this head start, they could have easily grown to 10^9 or 10^{10} solar masses, thereby producing the ancient quasars that have puzzled astronomers for nearly two decades.

The question is whether this scenario actually happened. Luckily, the James Webb Space Telescope (JWST) is due to launch later this year, and we should be able to find out.

THE FIRST SEEDS

BLACK HOLES ARE ENIGMATIC astronomical objects, areas where the gravity is so immense that it has warped spacetime so that not even light can escape. It was not until the detection of quasars, which allow astronomers to see the light emitted by matter falling into black holes, that we had evidence that they were real objects and not just mathematical curiosities predicted by Einstein's general theory of relativity.

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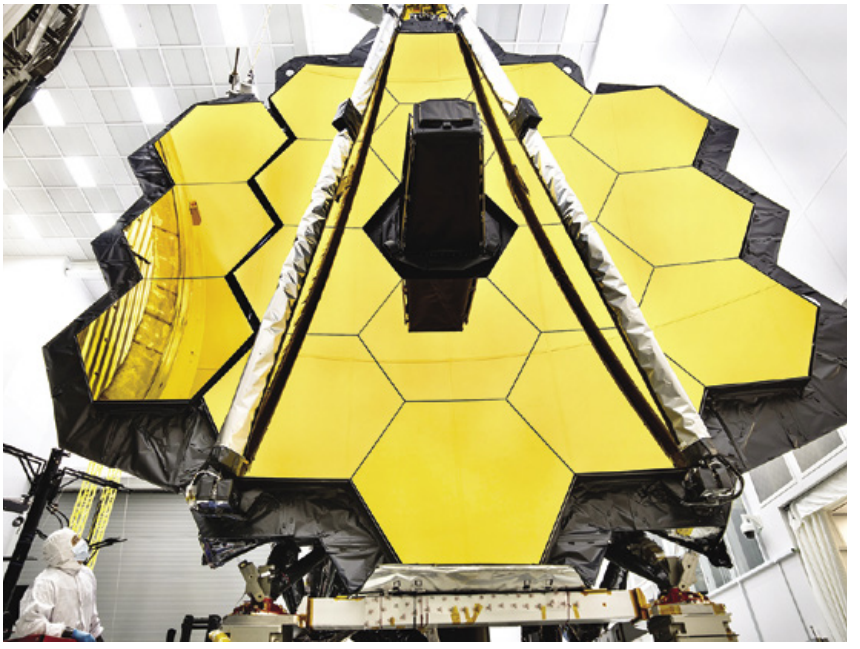
Most black holes are thought to form when very massive stars—those with more than about 10 times the mass of the sun—exhaust their nuclear fuel and begin to cool and therefore contract. Eventually gravity wins, and the star collapses, igniting a cataclysmic supernova explosion and leaving behind a black hole. Astronomers have traditionally assumed that most of the black holes powering the first quasars formed this way, too. They could have been born from the demise of the universe's first stars (Population III stars), which we think formed when primordial gas cooled and fragmented about 200 million years after the big bang. Population III stars were probably more massive than stars born in the later universe, which means they could have left behind black holes as hefty as several hundred solar masses. These stars also probably formed in dense clusters, so it is likely that the black holes created on their deaths would have merged, giving rise to black holes of several thousand solar masses. Even black holes this large, however, are far smaller than the masses needed to power the ancient quasars.



CHRIS GUNN NASA

DUE TO LAUNCH later this year, the James Webb Space Telescope will be powerful enough to find evidence for direct-collapse black holes, if they exist.

Theories also suggest that so-called primordial black holes could have arisen even earlier in cosmic history, when spacetime may have been expanding exponentially in a process called inflation. Primordial black holes could have coalesced from tiny fluctuations in the density of the universe and then grown as the universe expanded. Yet these seeds would weigh only between 10 and 100 solar masses, presenting the same problem as Population III remnants.

As an explanation for the first quasars, each of these pathways for the formation of black hole seeds has the same problem: the seeds would have to grow extraordinarily quickly within the first billion years of cosmic history to create the earliest quasars. And what we know about the growth of black holes tells us that this scenario is highly unlikely.

FEEDING A BLACK HOLE

OUR CURRENT UNDERSTANDING of physics suggests that there is an optimal feeding rate, known as the Eddington rate, at which black holes gain mass most efficiently. A black hole feeding at the Eddington rate would grow exponentially, doubling in mass every 10^7 years or so. To grow to 10^9 solar masses, a black hole seed of 10 solar masses would have to gobble stars and gas unimpeded at the Eddington rate for a billion years. It is hard to explain how an entire population of black holes could continuously feed so efficiently.

In effect, if the first quasars grew from Population III black hole seeds, they would have had to eat faster than the Eddington rate. Surpassing that rate is theoretically possible under special circumstances in dense, gas-rich environments, and these conditions may have been available in the early universe, but they would not have been common, and they would have been short-lived. Furthermore, exceptionally fast growth can actually cause "choking," where the radiation emitted during these super-Eddington episodes could disrupt and even stop the flow of mass onto the black hole, halting its growth. Given these restrictions, it seems that extreme feasting could account for a few freak quasars, but it cannot explain the existence of the entire detected population unless our current understanding of the Eddington rate and black hole feeding process is wrong.

Thus, we must wonder whether the first black hole seeds could have formed through other channels. Building on the work of several other research groups, my collaborator Giuseppe Lodato and I published a set of papers in 2006 and 2007 in which we proposed a novel mechanism that could have produced more massive black hole seeds from the get-go. We started with large, pristine gas disks that might otherwise have cooled and fragmented to give rise to stars and become galaxies. We showed that it is possible for these disks to circumvent this conventional process and instead collapse into dense clumps that form seed black holes weighing 10^4 to 10^6 solar masses. This outcome can occur if something interferes with the normal cooling process that leads to star formation and instead drives the entire disk to become unstable, rapidly funneling matter to the center, much like water flowing down a bathtub drain when you pull the plug.

Disks cool down more efficiently if their gas includes some molecular hydrogen—two hydrogen atoms bonded together—rather than atomic hydrogen, which consists of only one atom. But if radiation from stars in a neighboring galaxy strikes the disk, it can destroy molecular hydrogen and turn it into atomic hydrogen, which suppresses cooling, keeping the gas too hot to form stars. Without stars, this massive irradiated disk could

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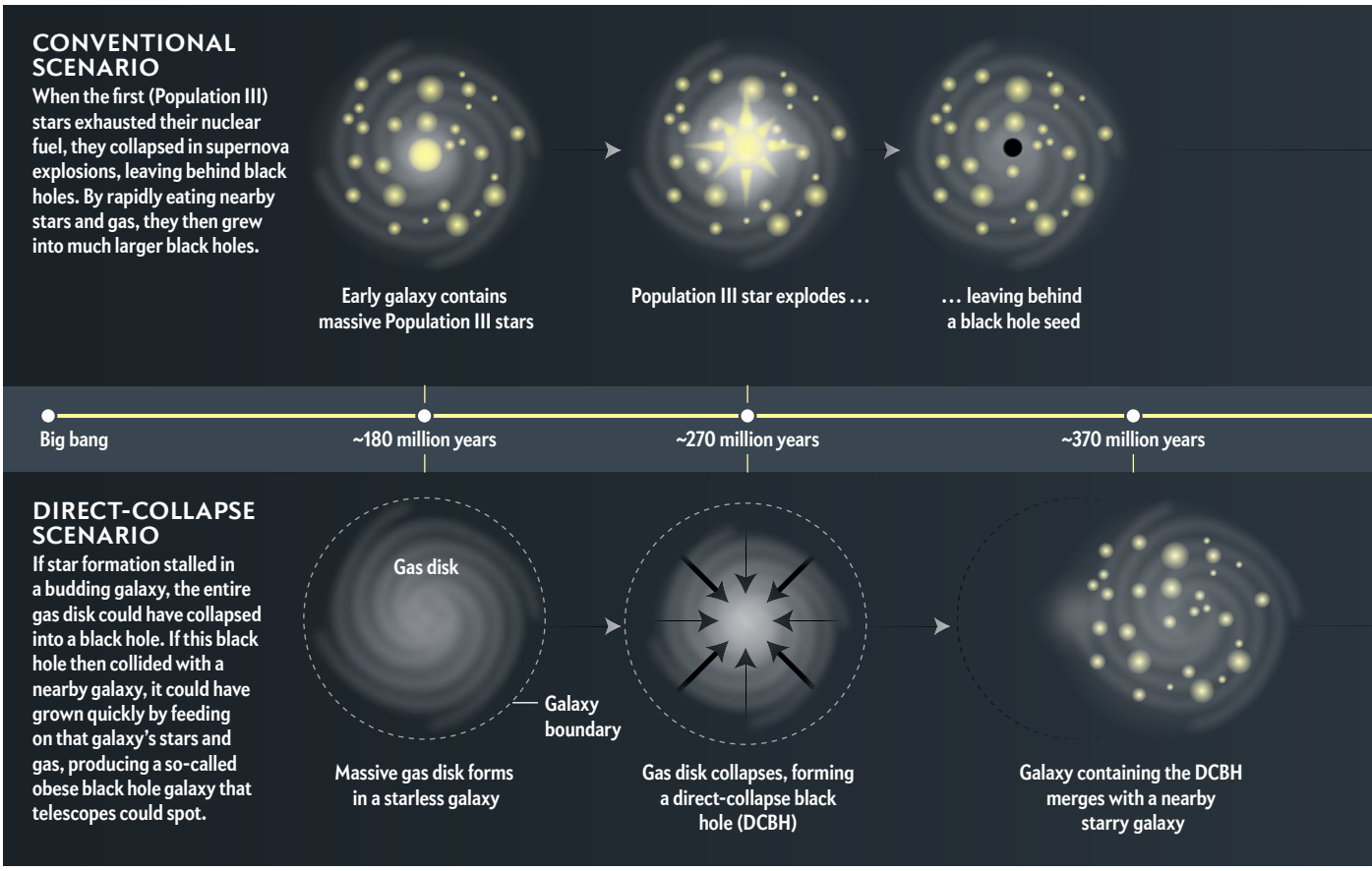
CONVENTIONAL SCENARIO
When the first (Population III) stars exhausted their nuclear fuel, they collapsed in supernova explosions, leaving behind black holes. By rapidly eating nearby stars and gas, they then grew into much larger black holes.
Early galaxy contains massive Population III stars
Population III star explodes . . .
. . . leaving behind a black hole seed
Big bang
~180 million years
~270 million years
~370 million years
DIRECT-COLLAPSE SCENARIO
If star formation stalled in a budding galaxy, the entire gas disk could have collapsed into a black hole. If this black hole then collided with a nearby galaxy, it could have grown quickly by feeding on that galaxy's stars and gas, producing a so-called obese black hole galaxy that telescopes could spot.
Gas disk
Galaxy boundary
Massive gas disk forms in a starless galaxy
Gas disk collapses, forming a direct-collapse black hole (DCBH)
Galaxy containing the DCBH merges with a nearby starry galaxy

become dynamically unstable, and matter would quickly drain into its center, rapidly driving the production of a massive, direct-collapse black hole. Because this scenario depends on the presence of nearby stars, we expect DCBHs to typically form in satellite galaxies that orbit around larger parent galaxies where Population III stars have already formed.

Simulations of gas flows on large scales, as well as the physics of small-scale processes, support this model for DCBH formation. Therefore, the idea of very large initial seeds appears feasible in the early universe. And starting with seeds in this range alleviates the timing problem for the production of the supermassive black holes that power the brightest, most distant quasars.

LOOKING FOR PROOF

BUT JUST BECAUSE DCBH SEEDS are feasible does not mean they actually exist. To find out, we must search for observational evidence. These objects would appear as bright, miniature quasars shining through the early universe. They should be detectable during a special phase when the seed merges with the parent galaxy—and this process should be common, given that DCBHs probably form in satellites orbiting larger galaxies. A merger would give the black hole seed a copious new source of gas to eat, so the black hole should start growing rapidly. In fact, it would briefly turn into a special kind of quasar that outshines all the stars in the galaxy.

These black holes will not only be brighter than their surrounding stars, they will also be heavier—a reversal of the usual order of things. In general, the stars in a galaxy outweigh the central black holes by about a factor of 1,000. After the galaxy hosting the DCBH merges with its parent galaxy, however, the mass of the growing black hole will briefly exceed that of the stars. Such an object, called an obese black hole galaxy, should have a very special spectral signature, particularly in the infrared wavelengths between one and 30 microns where the JWST's Mid-Infrared Instrument (MIRI) and Near-Infrared Camera (NIRCam) will operate. This telescope will be the most powerful tool astronomers have ever had for peering into the earliest stages of cosmic history. If the telescope detects these obese black hole galaxies, it will provide strong evidence for our DCBH theory. Traditional black hole seeds, on the other hand, which derive from dead stars, are likely to be too faint for the JWST or other telescopes to see.

It is also possible that we might find other evidence for our theory. In the rare case that the parent galaxy that merges with the DCBH also hosts a central black hole, the two holes will collide and release powerful gravitational waves. These waves could be detectable by the Laser Interferometer Space Antenna (LISA), a European Space Agency/NASA mission expected to fly in the 2030s.

A FULLER PICTURE

IT IS ENTIRELY POSSIBLE that both the DCBH scenario and small seeds feeding at super-Eddington rates both occurred in

Illustration by Amanda Montañez

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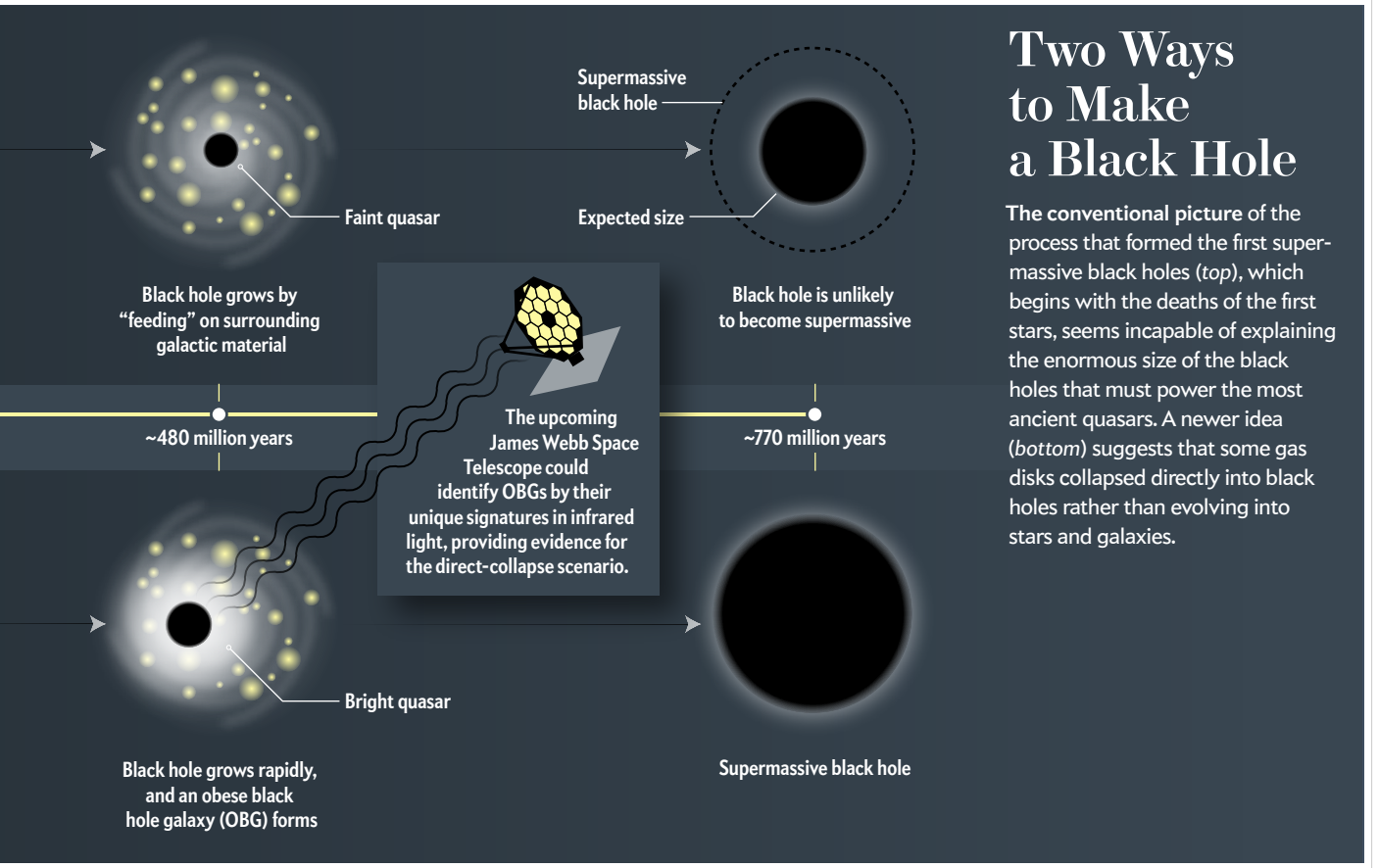
Supermassive black hole
Faint quasar
Expected size
Black hole grows by "feeding" on surrounding galactic material
Black hole is unlikely to become supermassive
~480 million years
~770 million years
The upcoming James Webb Space Telescope could identify OBGs by their unique signatures in infrared light, providing evidence for the direct-collapse scenario.
Bright quasar
Black hole grows rapidly, and an obese black hole galaxy (OBG) forms
Supermassive black hole

Two Ways to Make a Black Hole

The conventional picture of the process that formed the first supermassive black holes (*top*), which begins with the deaths of the first stars, seems incapable of explaining the enormous size of the black holes that must power the most ancient quasars. A newer idea (*bottom*) suggests that some gas disks collapsed directly into black holes rather than evolving into stars and galaxies.

the early universe. In fact, the initial black hole seeds probably formed via both these pathways. The question is: Which channel created the bulk of the bright ancient quasars that astronomers see? Solving this mystery could do more than just clear up the time line of the early cosmos. Astronomers also want to understand more broadly how supermassive black holes affect the larger galaxies around them.

Data suggest that central black holes might play an important role in adjusting how many stars form in the galaxies they inhabit. For one thing, the energy produced when matter falls into the black hole may heat up the surrounding gas at the center of the galaxy, thus preventing cooling and halting star formation. This energy may even have far-reaching effects outside the galactic center by driving energetic outflows. I predicted the existence of ghostly shadows that these quasar outflows would imprint on the relic radiation from the big bang in 1999; radio astronomers reported the first detection in December 2018. These winds likely heat up gas in outer regions and shut down star formation there. These effects are complex, however, and they stand to corroborate our current picture of black hole formation and growth. Finding the first seed black holes could help reveal how the relation between black holes and their host galaxies evolved over time.

These insights fit into a larger revolution in our ability to study and understand all masses of black holes. When the Laser Interferometer Gravitational-wave Observatory (LIGO) made the first detection of gravitational waves in 2015, for instance, scientists were able to trace them back to two colliding black holes weighing 36 and 29 solar masses, the lightweight cousins of the supermassive black holes that power quasars. The project continues to detect waves from similar events, offering new and incredible details about what happens when these black holes crash and warp the spacetime around them.

Another project called the Event Horizon Telescope, which uses radio observatories scattered around Earth to image the supermassive black hole at the center of the Milky Way, reported its first findings in 2019. Scientists spotted a ringlike shadow around the black hole's boundary—a feature that general relativity predicts will occur as a black hole's strong gravity deflects light. If any future Event Horizon Telescope measurements show deviations from the predictions of general relativity, they will have the potential to challenge our understanding of black hole physics. In addition, experiments looking at pulsing stars called pulsar timing arrays could also detect tremors in spacetime caused by an accumulated signal of many collisions of black holes. And eventually the JWST will open up an entirely new window on the very first black holes to light up the universe.

Many revelations are in store in the very near future, and our understanding of black holes stands to be transformed. SA

Priyamvada Natarajan is a theoretical astrophysicist at Yale University whose research focuses on cosmology, gravitational lensing and black hole physics.

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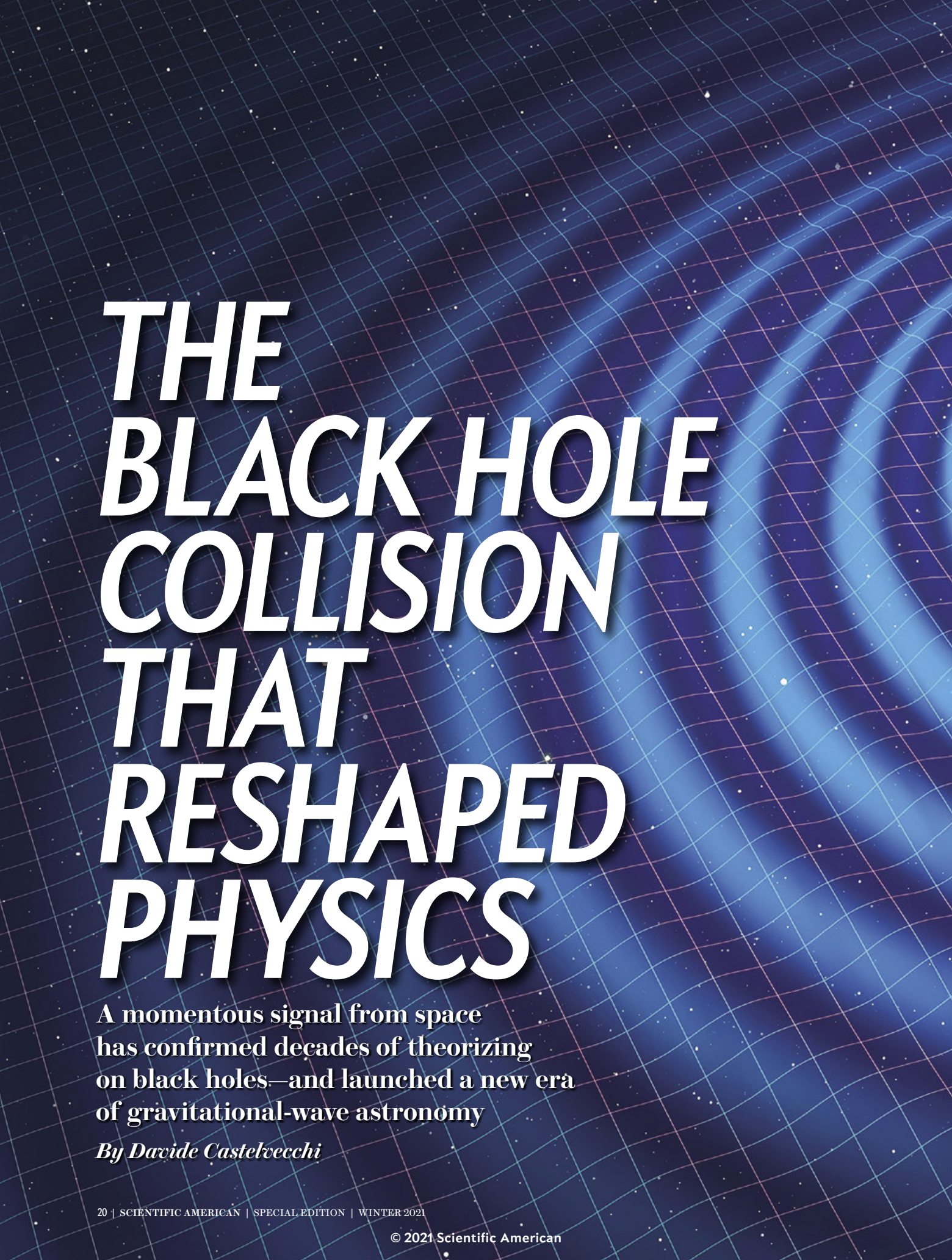

THE BLACK HOLE COLLISION THAT RESHAPED PHYSICS

A momentous signal from space has confirmed decades of theorizing on black holes—and launched a new era of gravitational-wave astronomy

By Davide Castelvecchi

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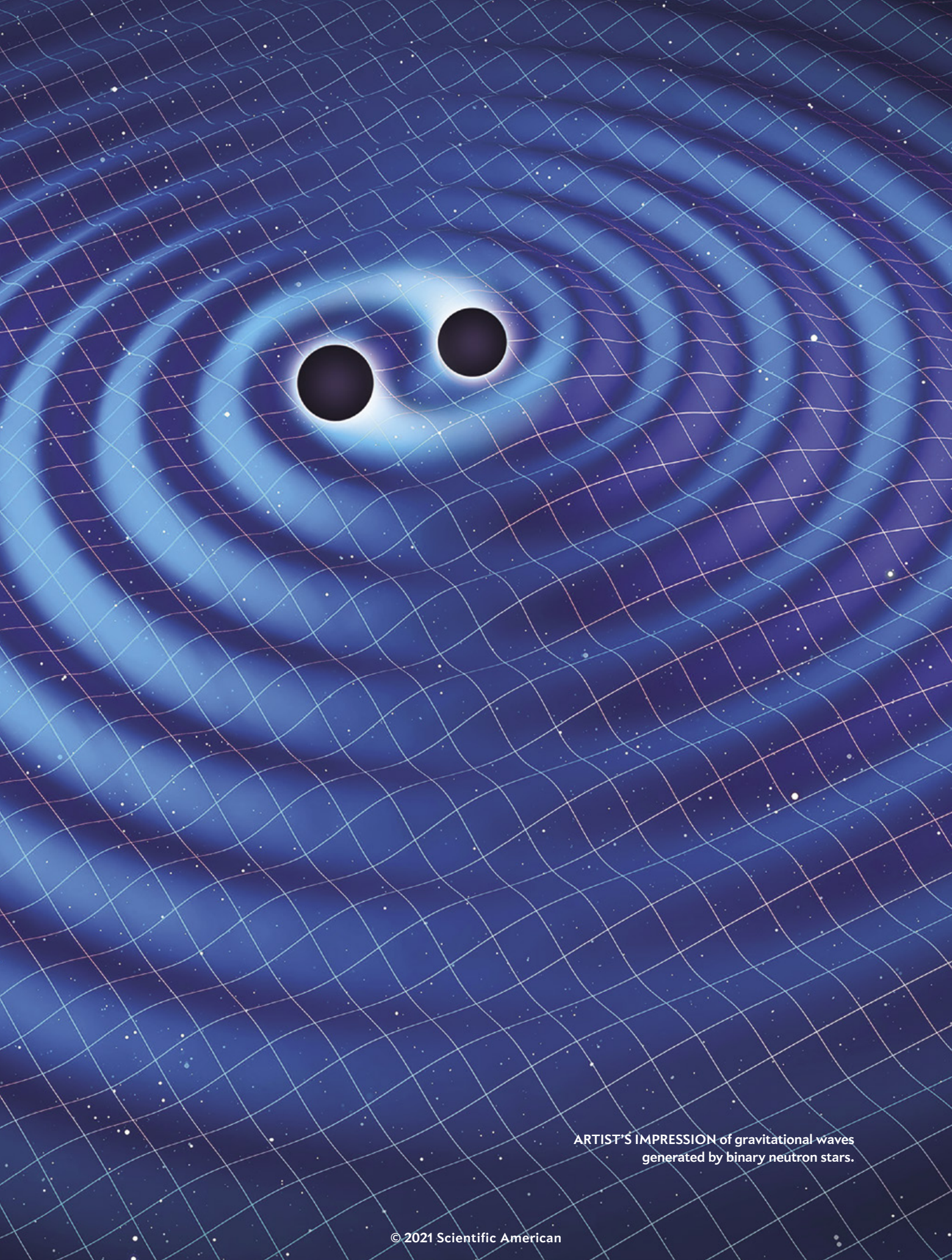

ARTIST'S IMPRESSION of gravitational waves generated by binary neutron stars.

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THE EVENT WAS CATASTROPHIC ON A COSMIC SCALE—A MERGER OF BLACK HOLES that violently shook the surrounding fabric of space and time and sent a blast of spacetime vibrations known as gravitational waves rippling across the universe at the speed of light. But it was the kind of calamity that physicists on Earth had been waiting for. On September 14, 2015, when those ripples swept across the freshly upgraded Laser Interferometer Gravitational-wave Observatory (Advanced LIGO), they showed up as spikes in the readings from its two L-shaped detectors in Louisiana and Washington State. For the first time ever, scientists had recorded a gravitational-wave signal.

"There it was!" says LIGO team member Daniel Holz, an astrophysicist at the University of Chicago. "And it was so strong, and so beautiful, in both detectors." Although the shape of the signal looked familiar from the theory, Holz says, "it's completely different when you see something in the data. It's this transcendent moment."

The signal, formally designated GW150914 after the date of its occurrence and informally known to its discoverers as "the Event," was justly hailed as a milestone in physics. It has provided a wealth of evidence for Albert Einstein's century-old general theory of relativity, which holds that mass and energy can warp spacetime and that gravity is the result of such warping. Stuart Shapiro, a specialist in computer simulations of relativity at the University of Illinois at Urbana-Champaign, calls it "the most significant confirmation of the general theory of relativity since its inception."

But the Event also marked the start of a long-promised era of gravitational-wave astronomy. Detailed analysis of the signal has already yielded insights into the nature of the black holes that merged, as well as how they formed. With more events such as these—LIGO and its European counterpart, the Franco-Italian-led Advanced Virgo facility near Pisa, Italy, have collected four dozen more since then—researchers will be able to classify and understand the origins of black holes, just as they are doing with stars.

Still more events will appear in future years as the freshly built Kamioka Gravitational-wave Detector (KAGRA) in Japan joins the search. (The three collaborations will pool their data and publish papers together.) Having more detectors not only will contribute crucial details to events but also could help astronomers make cosmological-distance measurements more accurately than before.

"It's going to be a really good ride for the next few years," says Bruce Allen, who is director of the Max Planck Institute for Gravitational Physics in Hanover, Germany.

"The more black holes they see whacking into each other, the more fun it will be," says theoretical physicist and mathematician Roger Penrose, emeritus professor at the University of Oxford, whose seminal work on black holes in the 1960s earned him a Nobel Prize in 2020. "Suddenly we have a new way of looking at the universe."

A MATTER OF ENERGY

PHYSICISTS HAVE KNOWN for decades that every pair of orbiting bodies is a source of gravitational waves. With each revolution, according to Einstein's equations, the waves will carry away a tiny fraction of their orbital energy. This will cause the objects to move a bit closer together and orbit a little faster. For familiar pairs, such as the moon and Earth, such energy loss is imperceptible even on timescales of billions of years.

But dense objects in very close orbits can lose energy much more quickly. In 1974 radio astronomers Russell Hulse and Joseph Taylor, then at the University of Massachusetts Amherst, found just such a system: a pair of dense neutron stars in orbit around each other. As the years went by, the scientists found that this "binary pulsar" was losing energy and spiraling inward exactly as predicted by Einstein's theory.

The two black holes detected by LIGO had probably been losing energy in this way for millions, if not billions, of years before they reached the end. But LIGO did not register the gravitational waves coming from them until 9:50:45 Coordinated Universal Time on September 14, 2015, when the waves' frequency rose above some 30 cycles per second (hertz)—corresponding to 15 full black hole orbits per second—and was finally high enough for the detectors to distinguish it from background noise.

But then, in just 0.2 second, LIGO watched the signal surge to 250 hertz and suddenly disappear as the black holes made their final five orbits, reached orbital velocities of half the speed of light and coalesced into a single massive object [*see box on opposite page*].

The LIGO and Virgo teams soon went to work extract-

PRECEDING PAGES: MARK GARLICK *Alamy*

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ing every bit of information possible. At the most fundamental level, the signal gave them an existence proof: the fact that the objects came so close to each other before merging meant that they had to be black holes because ordinary stars would need to be much bigger. "It is, I think, the clearest indication that black holes are really there," Penrose says.

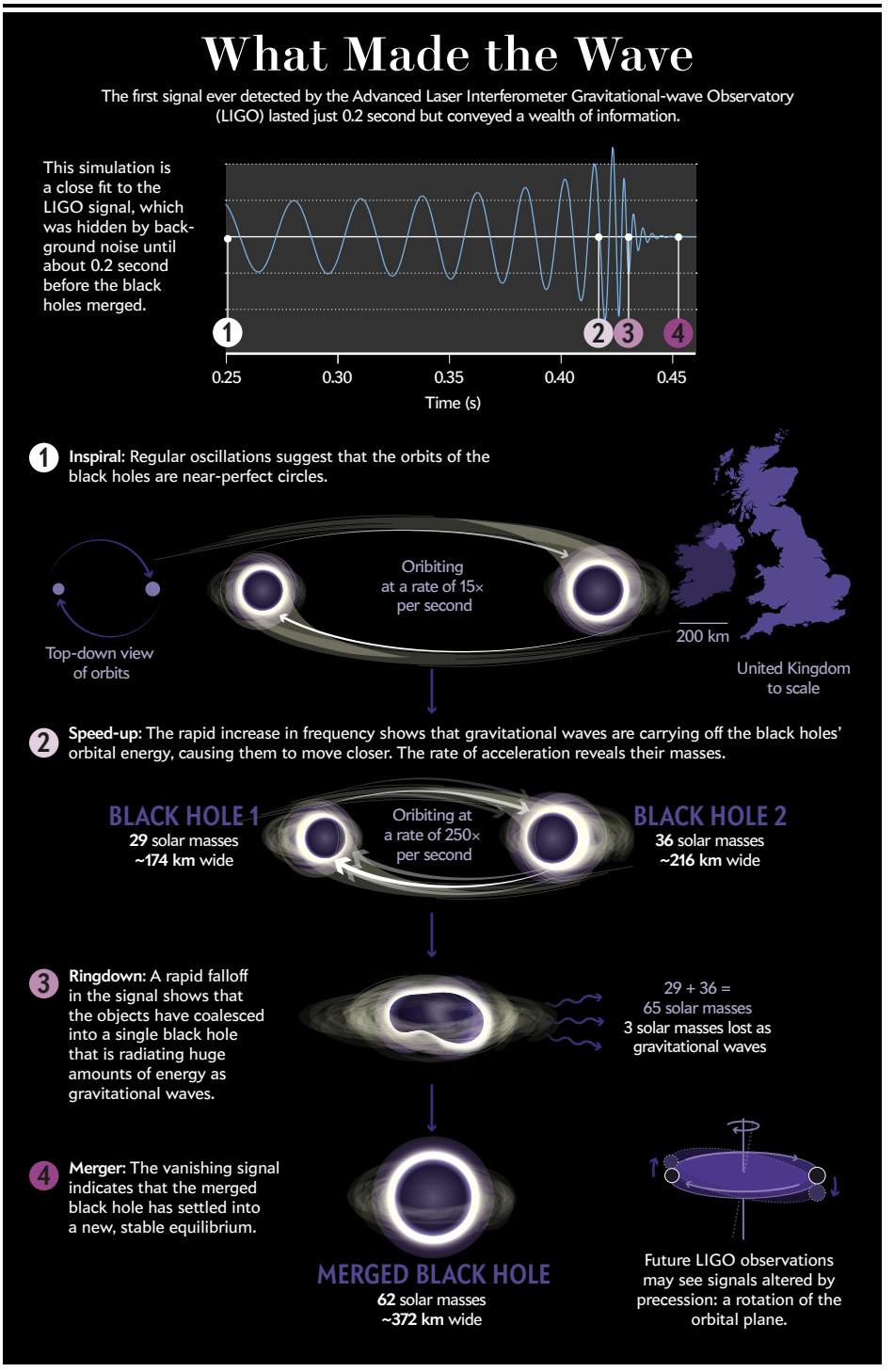
The signal also provided researchers with the first empirical test of general relativity beyond regions—including the space around the binary pulsar—where there is comparatively little spacetime warping. There was no empirical evidence that the theory would keep its validity at the extreme energies of merging black holes, Shapiro says—but it did.

The signal held a trove of more detailed information as well. By scrutinizing its shape just before the final cataclysm, the scientists found that it closely approximated a simple sine wave with a steadily increasing frequency and amplitude. According to B. S. Sathyaprakash, a theoretical physicist at Pennsylvania State University and a senior LIGO researcher, this pattern suggests that the orbits of the black holes were nearly circular and that LIGO probably had a bird's-eye view of the circles, looking almost straight down on them rather than edge-on.

In addition, the LIGO and Virgo teams were able to use the frequency of the observed wave, along with its rate of acceleration, to estimate the masses of the two black holes: because heavier objects radiate energy in the form of gravitational waves at a faster rate than do lighter objects, their pitch rises more quickly.

By recreating the Event with computer simulations, the scientists calculated that the two black holes weighed about 36 times and 29 times the mass of the sun, respectively, and that the combined black hole weighed about 62 solar masses. The lost difference, about three suns' worth, was dispersed as gravitational radiation—much of it during what physicists call the ringdown phase, when the merged black hole was settling into a spherical shape. (For comparison, the most powerful thermonuclear bomb ever detonated converted only about two kilograms of matter into energy—roughly 10^{30} times less.) The teams also suspect that the final black hole was spinning at perhaps 100 revolutions per second, although the margin of error on that estimate is large.

The inferred masses of the two black holes are also revealing. Each object was presumably the remnant of a very massive star, with the larger star approaching 100 times the mass of the sun and the smaller one a lit-


What Made the Wave
The first signal ever detected by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) lasted just 0.2 second but conveyed a wealth of information.
This simulation is a close fit to the LIGO signal, which was hidden by background noise until about 0.2 second before the black holes merged.
1
2
3
4
0.25
0.30
0.35
0.40
0.45
Time (s)
1 Inspiral: Regular oscillations suggest that the orbits of the black holes are near-perfect circles.
Top-down view of orbits
Oribiting at a rate of 15× per second
200 km
United Kingdom to scale
2 Speed-up: The rapid increase in frequency shows that gravitational waves are carrying off the black holes' orbital energy, causing them to move closer. The rate of acceleration reveals their masses.
BLACK HOLE 1
29 solar masses
~174 km wide
Oribiting at a rate of 250× per second
BLACK HOLE 2
36 solar masses
~216 km wide
3 Ringdown: A rapid falloff in the signal shows that the objects have coalesced into a single black hole that is radiating huge amounts of energy as gravitational waves.
29 + 36 = 65 solar masses
3 solar masses lost as gravitational waves
4 Merger: The vanishing signal indicates that the merged black hole has settled into a new, stable equilibrium.
MERGED BLACK HOLE
62 solar masses
~372 km wide
Future LIGO observations may see signals altered by precession: a rotation of the orbital plane.

NIK SPENCER *Nature*: "THE BLACK-HOLE COLLISION THAT RESHAPED PHYSICS," BY DAVIDE CASTELVECCHI, IN *NATURE*, VOL. 531; MARCH 24, 2016; DOI:10.1038/531428A (*graphic*); SOURCE: "OBSERVATION OF GRAVITATIONAL WAVES FROM A BINARY BLACK HOLE MERGER," BY B. P. ABBOTT ET AL., IN *PHYSICAL REVIEW LETTERS*, VOL. 116; FEBRUARY 12, 2016 (*reference material*)

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tle less. Thermonuclear reactions are known to convert hydrogen in the cores of such stars into helium much faster than in lighter stars, which leads them to collapse under their own weight only a few million years after they are born. The energy released by this collapse causes an explosion called a type II supernova, which leaves behind a residual core that turns into a neutron star or, if it is massive enough, a black hole.

Scientists say that type II supernovae should not produce black holes much bigger than about 30 solar masses—and both black holes were at the high end of that range. This could mean that the system formed from interstellar gas clouds that were richer in hydrogen and helium than the ones typically found in our galaxy and that were poorer in heavy elements, which astronomers call metals.

"THE MORE BLACK HOLES THEY SEE WHACKING INTO EACH OTHER, THE MORE FUN IT WILL BE. SUDDENLY, WE HAVE A NEW WAY OF LOOKING AT THE UNIVERSE."
—ROGER PENROSE *UNIVERSITY OF OXFORD*

Astrophysicists have calculated that stars formed from such low-metallicity clouds should have an easier time forming massive black holes when they explode, explains Gijs Nelemans, an astronomer at Radboud University Nijmegen in the Netherlands and a member of the Advanced Virgo collaboration. That is because during a supernova explosion, smaller atoms are less likely to be blown away by the blast. Low-metallicity stars thus "lose less mass, so more of it goes into the black hole, for the same initial mass," Nelemans says.

TWO BY TWO

BUT HOW DID THESE two black holes end up in a binary system? In a paper published at the same time as the one reporting the 2015 discovery, the LIGO and Virgo teams described two commonly accepted scenarios.

The simplest one is that two massive stars were born as a binary-star system, formed from the same interstellar gas cloud like a double-yolked egg, and have been orbiting each other ever since. (Such binary stars are common in our galaxy; singletons such as the sun are the exception rather than the rule.) After a few million years, one of the stars would have burned out and gone supernova, soon to be followed by the other. The result would be a binary black hole.

The second scenario is that the stars formed independently but still inside the same dense stellar cluster—perhaps one similar to the globular clusters that orbit the Milky Way. In such a cluster, massive stars would sink toward the center and, through complex interactions with lighter stars, form binary systems, possibly long after their transformation into black holes.

Simulations made by Simon Portegies Zwart, an astrophysicist at Leiden University in the Netherlands, show that massive stars are more likely to form in dense clusters, where collisions and mergers are more common. He also finds that once a binary black hole system forms, the complex dynamics of the cluster's center will probably kick the pair out at high speed. The binary that Advanced LIGO detected may have wandered away from any galaxy for billions of years before merging, he says.

Although the LIGO and Virgo teams were able to learn a lot from the Event, there is much more that gravitational waves could teach them, even in the case of black hole mergers. The detectors showed that immediately after the black holes merged, the waves quickly died down as the resulting black hole settled into a symmetrical shape. This is consistent with predictions made by the late theoretical physicist C. V. Vishveshwara in the early 1970s, a time when "gravitational waves and black holes both belonged to the realm of mythology," Vishveshwara said in 2016. "At that time, I had not imagined that it would ever be verified."

But LIGO saw just slightly more than one cycle of the Event's ringdown waves before the signal became buried once more in the background noise—not yet enough data to provide a rigorous test of Vishveshwara's predictions.

More stringent tests will be possible if and when LIGO detects black hole mergers that are larger than this one or that occur closer to Earth than the Event's estimated distance of 1.3 billion light-years and therefore that give "louder" waves that stay above the noise for longer.

Alessandra Buonanno, a LIGO theorist and director of the Max Planck Institute for Gravitational Physics in Potsdam-Golm, Germany, says that a more detailed picture of the ringdown stage could reveal how fast the final black hole rotates, as well as whether its formation gave it a "natal kick" imparting a high velocity.

In addition, Sathyaprakash says, "we are especially waiting for systems that are much lighter, so they last longer." Such events include the mergers of lighter binary black holes, of binary neutron stars or of a black hole with a neutron star. Each type delivers its own signature chirp and could produce a signal that stays above LIGO's threshold of sensitivity for several minutes or more.

"GW150914 is in some sense a very vanilla system," says Chad Hanna, a LIGO member at Pennsylvania State University. "It's beautiful, of course, but it doesn't have all the crazy things that one might expect."

SPACE ARTISTRY

ONE PHENOMENON that Sathyaprakash is eager to observe is a "precession" of the black holes' orbital plane, meaning that their paths trace a kind of three-dimensional rosette. This is a relativistic effect that has no counterpart in Newtonian gravity, and it should pro-

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duce a characteristic fluctuation in the strength of the gravitational waves. But orbital precession occurs only when two black holes have axes of rotation that point in random directions, and it disappears when the axes are both perpendicular to the orbital plane. The occurrence of a precession provides clues to how the black holes formed.

It is hard to be sure about that possibility because there are many uncertainties in simulating supernovae. But astrophysicists suspect that parallel spins generally signify that the original two stars were born together out of the same whirling gas cloud. Similarly, they think that random spins result from black holes that formed separately and later fell into orbit around each other. Once the observatories find more mergers, they may be able to determine which type of system occurs more frequently.

Although detecting more events will help LIGO to do lots of science, its interferometers have intrinsic limitations that make it necessary to work together with a worldwide network of similar detectors.

First, LIGO's two interferometers are not enough for scientists to determine precisely where the waves came from. The researchers can get some information by comparing the signal's time of arrival at each detector: the difference enables them to calculate the wave's direction relative to an imaginary line drawn between the two. But in the case of the Event, which recorded a difference of 6.9 milliseconds, their calculations limited the field of possibilities merely to a wide strip of southern sky.

After Virgo got online in August 2017, the scientists were able to narrow down the direction substantially by comparing the waves' arrival times at three places. And with the recent addition of KAGRA in Japan, their precision will improve even more. India also has its own LIGO in planning stages.

Knowing an event's direction also helps to remove one of the biggest uncertainties in determining its distance from Earth. Waves that approach from a direction exactly perpendicular to the detector—either from above or from below, through Earth—are recorded at their actual amplitude, explains Fulvio Ricci, a physicist at the Scuola Normale Superiore in Pisa, Italy, and a former spokesperson for Virgo. Waves that come from elsewhere in the sky, however, will hit the detector at an angle and produce a somewhat smaller signal, according to a known formula. There are even some blind spots where a source cannot be seen by a given detector at all.

Determining the direction reveals the exact amplitude of the waves. By comparing that figure with the waves' amplitude at the source, which the researchers are able to derive from the shape of the signal, and by knowing how the amplitude decreases with distance, which they get from Einstein's theory, they can then calculate the distance of the source with much greater precision.

This situation is almost unprecedented: conventionally, astronomical distances need to be estimated by looking at the brightness of known objects in locations that range from the solar system to distant galaxies. But the measured brightness of those "standard candles" can be dimmed by stuff in between. Gravitational waves have no such limitation.

RAISING THE ALARM

THERE IS ANOTHER important reason that scientists are eager to have precise estimates of the waves' provenance. The LIGO and Virgo teams have arranged to give near-real-time alerts of intriguing events to conventional astronomers, who can use their optical, radio and space-based telescopes to see whether those events produced any form of electromagnetic radiation. In return, the LIGO and Virgo collaborations will be sifting through data to search for gravitational waves that could have been generated by events, such as supernova explosions, seen by the conventional observatories.

Some 20 teams tried to follow up on the Event, mostly to no avail. NASA's Fermi Gamma-ray Space Telescope did see a possible burst of gamma rays about 0.4 second later, coming from an equally vague but compatible region of the southern sky. But most observers now consider it to be a coincidence. Such gamma rays could, in principle, have been produced when gas orbiting the binary black hole was heated up during the merger, says Vicky Kalogera, a LIGO astrophysicist at Northwestern University. But "our astrophysical expectation has been that the gas from stars that formed the binary black hole has long dispersed. There shouldn't be any significant gas around," she says.

In August 2017, however, the synergy between gravitational waves and conventional astronomy played out in spectacular fashion, when—following a gravitational signal spotted by LIGO and Virgo—more than 70 teams of astronomers were able to locate and observe the fireworks from a merger of two neutron stars.

Matching gravitational waves with electromagnetic ones has ushered in a new era of astronomy. In particular, the 2017 event confirmed that mergers of neutron stars are expected to produce short gamma-ray bursts. Researchers are then able to measure how far the light from those bursts is shifted toward the red end of the spectrum, which tells astronomers how fast the stars' host galaxies are receding because of the expansion of the universe.

Matching those redshifts to distance measurements calculated from gravitational waves also gives estimates of the current rate of cosmic expansion, known as the Hubble constant, that are independent of—and potentially more precise than—calculations using current methods. "From the point of view of measuring the Hubble constant, that's our gold-plated source," Holz says. "To be honest," he says, "I find it really hard to believe that the universe is really doing this stuff. But it's not science fiction. It really happened." SA

Davide Castelvecchi is a senior reporter at *Nature* in London covering physics, astronomy, mathematics and computer science.

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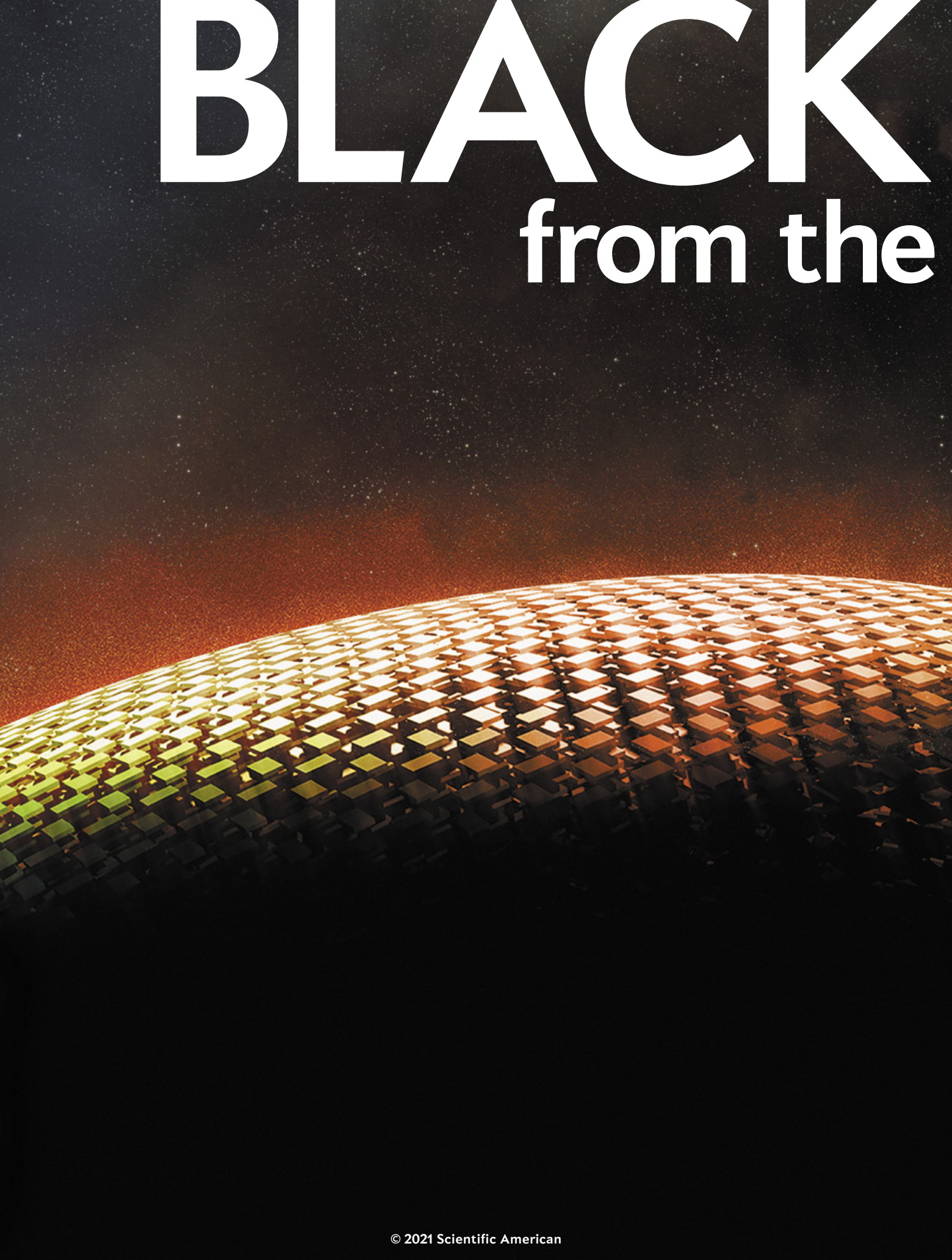
BLACK from the



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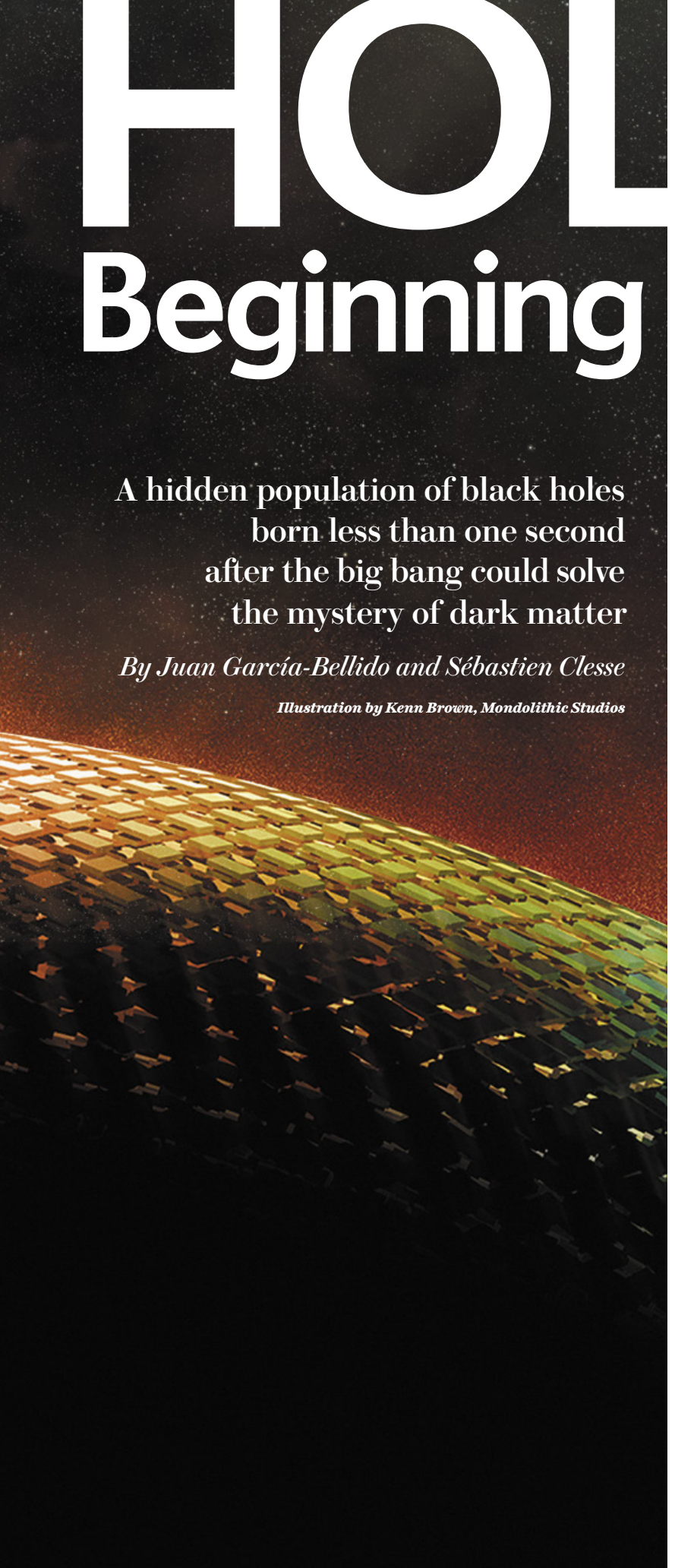
HOLES Beginning of Time



A hidden population of black holes born less than one second after the big bang could solve the mystery of dark matter

By Juan García-Bellido and Sébastien Clesse

Illustration by Kenn Brown, Mondolithic Studios

More than a billion years ago two black holes in the distant universe spiraled around each other in a deathly dance until they merged. This spiraling collision was so violent that it shook the fabric of space-time, sending perturbations—gravitational waves—rippling outward through the cosmos at the speed of light. In September 2015, after traveling more than a billion light-years, those ripples washed over our planet, registering as a "chirp" in the sensors of the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO).

This was the first direct detection of gravitational waves, and the observation confirmed Albert Einstein's century-old prediction of their existence. Yet the chirp revealed that each of the merger's progenitor black holes was 30 times heavier than the sun. That is, their masses were two to three times larger than ordinary black holes born from supernova explosions of massive stars. These black holes were so heavy, it is hard to explain how they formed from stars at all. Furthermore, even if two such black holes did independently form from the deaths of very massive stars, they would have then had to find each other and merge—an event with an exceedingly low probability of occurring within the current age of the universe. It is thus reasonable to suspect that these massive black holes formed via some other, more exotic pathway

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that might not involve stars at all. Beyond its detection of gravitational waves, it may be that LIGO has unveiled something even more extraordinary: black holes that predate the formation of the stars themselves.

Although such "primordial" black holes have never before been seen, some theoretical models suggest they could have formed in astronomical numbers from the hot, dense plasma that filled the cosmos less than one second after the big bang. This hidden population could solve several outstanding mysteries in modern cosmology. In particular, primordial black holes could constitute some, if not all, of dark matter—the invisible 85 percent of the matter in the universe that acts as gravitational glue to hold galaxies and galaxy clusters together. Further studies with LIGO and other facilities will soon test these ideas, potentially unleashing a new revolution in our understanding of the cosmos.

THE FALL OF MACHOS, THE RISE OF WIMPS

BLACK HOLES would initially seem to be ideal candidates for dark matter because they emit no light. Indeed, along with other dark objects such as planets and brown dwarfs, they make up one long-proposed solution to the dark matter problem: MACHOs, short for "massive compact halo objects." Found both in spherical halos surrounding each galaxy and near each galaxy's luminous center, MACHOs would create the gravitational pull responsible for the otherwise anomalous motions of stars and gas that astronomers observe in the outskirts of galaxies. Simply put, galaxies seem to be rotating too fast to be held together by the visible mass in stars that we observe. Dark matter provides the extra pull to prevent spinning galaxies from flinging off their stars.

If MACHOs make up most of the universe's dark matter, they must also account for other observations. Whatever dark matter is, it shapes the universe's largest structures, determining the origin and growth of galaxies, as well as that of galaxy clusters and superclusters. These objects coalesce from the gravitational collapse of clumps of gas inside dark matter halos. Cosmologists have precisely mapped the spatial distribution of these clumps through deep and wide galaxy surveys and correlated them with tiny temperature fluctuations present in the cosmic microwave background (CMB), the big bang's all-sky afterglow. The diffuse mass of dark matter in large galaxies and clusters also bends space to distort the light from far-distant background objects—a phenomenon known as gravitational lensing.

The MACHO hypothesis, however, fell from favor a decade ago, when MACHOs did not turn up in tentative, indirect searches for their existence. Most notably, astronomers looked for them via microlensing, a variety of gravitational lensing in which a black hole, a brown dwarf or even a planet passes in front of a background star and temporarily magnifies the star's light. Several multiyear microlensing surveys of millions of stars in the Large and Small Magellanic Clouds, the main satellite galaxies of the Milky Way, found no evidence that MACHOs made up the entirety of our galactic halo. These results were conclusive enough to rule out MACHOs up to around 10 solar masses as the primary constituent of dark matter. As these surveys took place, theorists built the case for an alternative hypothesis—WIMPs, or weakly interacting massive particles.

WIMPs are predicted by certain extensions of the Standard Model of particle physics, but they remain at least as elusive as MACHOs. To date, no evidence of their existence has been found despite decades of searches using particle accelerators, underground detectors and space telescopes. As null results piled up in the search for WIMPs, some researchers began reconsidering the MACHO hypothesis, focusing particularly on primordial black holes. But what process could have seeded these strange objects throughout the observable universe, and how could they have eluded detection for so long?

BLACK HOLES FROM THE BIG BANG

ASTRONOMER BERNARD CARR and the late physicist Stephen Hawking proposed the idea of primordial black holes in the 1970s. They considered black holes with masses smaller than that of a mountain. Such minuscule black holes would have already evaporated and vanished within the age of our nearly 14-billion-year-old universe, via a quantum-mechanical process discovered by Hawking and appropriately called Hawking radiation. But they also investigated the possibility that more massive, nonevaporating black holes could constitute the missing matter in galaxy clusters. The possibility that massive primordial black holes could actually be most or even all of the dark matter hinges on an idea known as cosmic inflation, first proposed by physicist Alan Guth in the early 1980s.

Inflation is a hypothetical phase of prodigious expansion immediately after the big bang. In 10^{-35} second, two points separated by less than an atomic radius would have become separated by four light-years, a distance comparable to that of the closest stars. Moreover, during inflation tiny quantum fluctuations are magnified to macroscopic scales by the rapid expansion, seeding the growing universe with underdense and overdense regions of matter and energy from which all cosmic structures subsequently emerge. As bizarre as it may seem, the theory of inflation is strongly supported by observations of such density fluctuations in the CMB.

In 1996 one of us (García-Bellido), together with Andrei Linde of Stanford University and David Wands of the University of Portsmouth in England, discovered a way for inflation to form sharp peaks in the spectrum of density fluctuations in the early universe [*see box on opposite page*]. That is, we showed how quantum fluctuations enormously magnified by inflation would naturally produce particularly dense regions that would collapse to form a population of black holes less than one second after inflation ends. Such black holes would then behave as dark matter and would dominate the matter content of the present-day universe. This model generated a population of black holes with the same mass, determined by the amount of energy within the collapsing region. Many other groups then started exploring these ideas within different models of inflation.

In 2015 the two of us (Clesse and García-Bellido) proposed a scenario, similar to that of 1996, in which these primordial fluctuations exhibit a broad peak in their energy densities and spatial sizes, giving rise to primordial black holes with a wide range of masses. A key consequence of this scenario is the fact that large density fluctuations collapse in close spatial proximity to one another, generating clusters of black holes of different masses—from one 100th to 10,000 times the mass of our sun. Within half a million years of the big bang, each growing,

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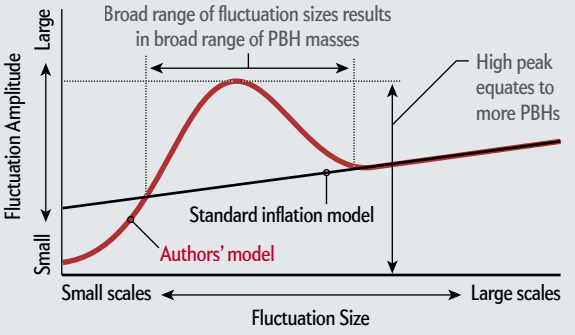
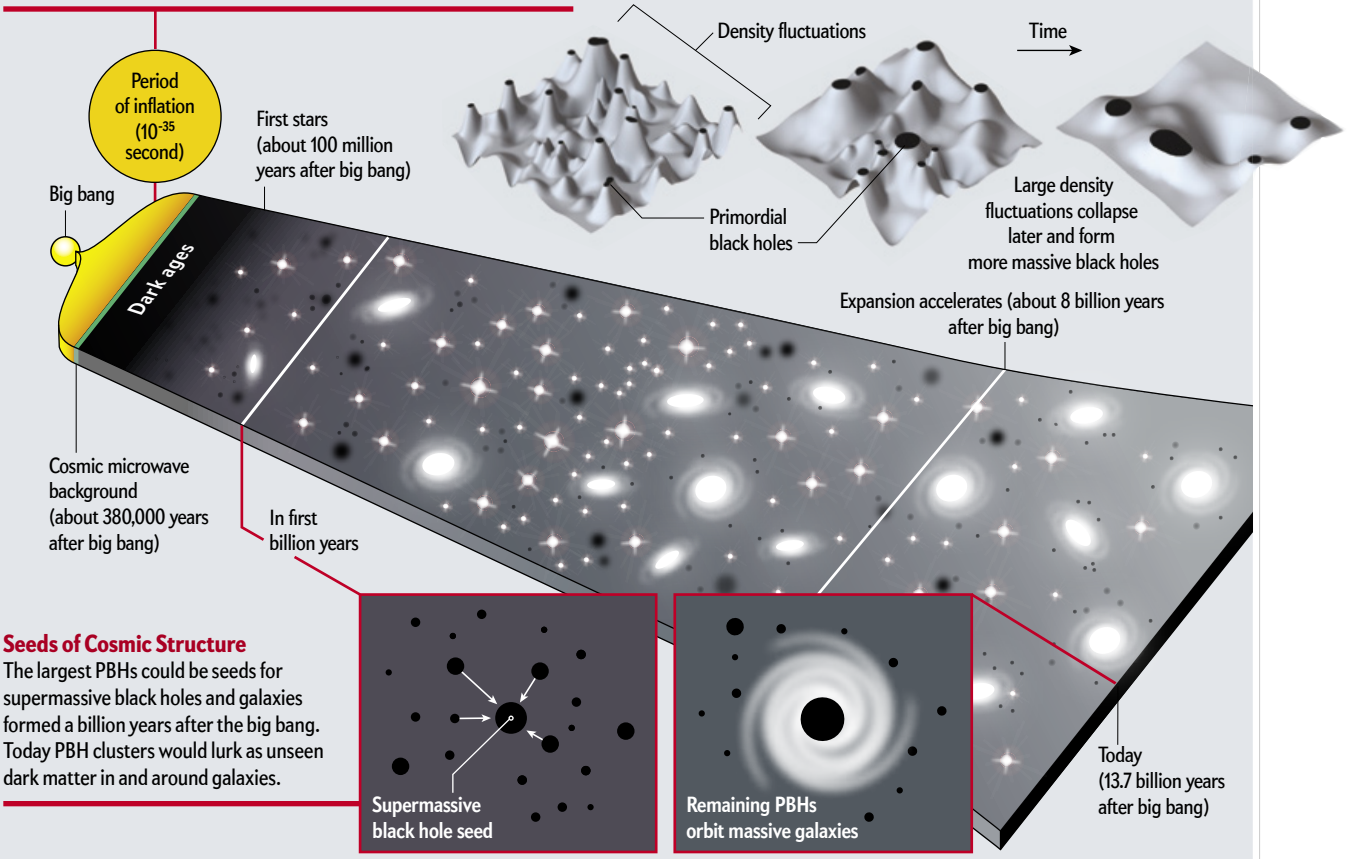
Black Holes Birthed by the Big Bang

The universe's first black holes may have been born in the earliest moments of cosmic time, when all was a seething, thick fog of fundamental particles. In the 1970s theorists realized that dense regions of that fog could collapse under their own gravity just a second after the big bang, forming so-called primordial black holes (PBHs) that would then shape the structure of the evolving, expanding universe. Emitting no light, PBHs would be a natural—albeit difficult-to-detect—candidate for dark matter.

Primordial Black Holes Form in Clusters

Inflation—a proposed acceleration to the universe's expansion less than a second after the big bang—would form PBHs by magnifying quantum fluctuations to immense scales. As inflation ended, these fluctuations would create density perturbations that would then form PBHs. Larger, more powerful fluctuations would create more massive and numerous PBHs. The authors' inflationary model predicts a broad peak of magnified fluctuations and a range of density perturbations, producing PBHs in clusters, with each PBH ranging from one 100th to 10,000 times the mass of our sun. Half a million years after the big bang, a cluster might span hundreds of light-years and contain millions of PBHs. As the PBHs within such clusters merged together, scattered apart, and fed on ordinary gas and dust, they would guide the growth of galaxies and galactic clusters.




Density fluctuations
Time
Period of inflation (10^{-35} second)
First stars (about 100 million years after big bang)
Big bang
Dark ages
Primordial black holes
Large density fluctuations collapse later and form more massive black holes
Expansion accelerates (about 8 billion years after big bang)
Cosmic microwave background (about 380,000 years after big bang)
In first billion years
Today (13.7 billion years after big bang)

Seeds of Cosmic Structure

The largest PBHs could be seeds for supermassive black holes and galaxies formed a billion years after the big bang. Today PBH clusters would lurk as unseen dark matter in and around galaxies.

evolving cluster could contain millions of primordial black holes in a volume just hundreds of light-years across.

Such clusters of primordial black holes would be sufficiently dense to explain LIGO's mysterious black hole mergers, which one would not otherwise expect to occur with regularity. From time to time, the trajectories of two primordial black holes within a cluster can cross, so that both objects become gravitationally bound to each other. They would then spiral closer together for up to millions of years, radiating gravitational waves until they merged. In January 2015 we actually predicted that LIGO would detect gravitational waves from such massive mergers—waves identical to those LIGO then detected later that year. Our estimates for the rate of merger events within primordial black hole clusters fit perfectly within the limits set

Illustration by Jen Christiansen and George Retseck (density-fluctuation panels)

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Is Dark Matter Made of Primordial Black Holes?

The quest for observational evidence continues

Seven observations point toward the hypothesis that primordial black holes constitute dark matter in the universe:

1. Mass, spin and merging rates of black holes. Gravitational-wave detectors are finding black hole mergers at a rate suggesting an abundance of black holes similar to the dark matter. In June 2017 LIGO announced the detection of black hole merger GW170104, for which the axis of rotation of one of the black hole progenitors was very likely not aligned with the axis of the orbital plane. This would be a sign that the black hole binary probably formed by a capture process, as expected for primordial black holes rather than from a preexisting star binary. Ultimately if we found a black hole with a mass lower than the so-called Chandrasekhar limit (1.4 solar masses, below which stars cannot produce a black hole), it would undeniably have a primordial origin. Fortunately, LIGO may very soon reach the sensitivity to detect such a black hole if its companion is more massive (greater than 10 solar masses). Finally, on cosmological scales, abundant black hole binaries should induce a diffuse background of gravitational waves, which could be detected by the future space-based Laser Interferometer Space Antenna (LISA) and by ground-based pulsar timing arrays.

2. Microlensing of stars in M31 and distant quasars. A broad mass distribution of primordial black holes, centered on a few solar masses, would perfectly explain not only the LIGO/Virgo gravitational-wave detections but also the microlensing of stars in the Andromeda galaxy (M31) and of distant quasars if they constitute dark matter. Such a model passes all the other cosmological and astrophysical constraints.

3. Ultrafaint dwarf galaxies. In 2015 astronomers using data from the Dark Energy Survey discovered dozens of ultrafaint dwarf galaxies in the galactic halo, suggesting that hundreds of such dark matter–dominated dwarf galaxies could orbit around the Milky Way. Strangely, none of them had a radius smaller than 50 light-years. Regular close encounters of primordial black holes with stars would make such dwarf galaxies unstable. On the other hand, a rapid accretion episode in the densest halos provides a new mechanism to explicate why some dwarf galaxies are strongly dominated by dark matter and others are not. Future space-based facilities such as the European Space Agency's Euclid mission and NASA's Wide-field Infrared Survey Telescope (WFIRST) should detect many more ultrafaint dwarf galaxies and so will test this hypothesis.

4. Galactic dark matter profiles. New observations suggest the dark matter distribution is more homogeneous near the center of galaxies of all sizes, which would hardly be explained by any known astrophysical processes such as supernovae feedback. Primordial black holes of several solar masses would naturally explain the existence of core dark matter profiles, thanks to gravitational scattering that homogenizes their distribution in the densest regions.

5. Correlations between x-ray and infrared backgrounds. Alexander Kashlinsky of NASA's Goddard Space Flight Center suggested that correlations between x-ray and infrared cosmic background fluctuations that could not be explained by any known population of galaxies would naturally arise if dark matter were made of massive primordial black holes. They would emit x-rays when they accreted matter in black hole clusters where a first generation of stars could also ignite and shine in infrared.

6. Billions of supermassive black holes. Recent observations by Chandra suggest that billions of supermassive black holes already existed one billion years after the big bang, shortly after the formation of the first stars. The required black hole seeds could have a primordial origin.

7. Unexpectedly cool universe at the time of star formation. In February 2018 a modest radio telescope built by a small team of astronomers at the Massachusetts Institute of Technology and at Arizona State University, called EDGES, might have detected the light from the epoch of formation of the first star generation, 200 million years after the big bang. Yet the amplitude of the signal was totally unexpected and suggests that the universe was half as warm—or colder—as in any realistic scenario. We are exploring whether primordial black hole dark matter could explain this observation, for instance, as an indirect effect of accretion of the neutral hydrogen gas. *—J.G.-B. and S.C.*

by LIGO. If LIGO and other similar facilities detect many more mergers, it may be possible to determine the range of masses and spins for all the progenitor black holes. Such a statistical analysis of black hole mergers would provide crucial information for testing their potentially primordial origins.

A key aspect of this scenario is that it evades the constraints on MACHOs previously set by gravitational microlensing experiments—constraints that ruled out black holes of up to about 10 solar masses as the main constituent of dark matter. If primordial black holes exist and possess a wide range of masses, only a small fraction will be visible to these microlensing experiments, with the bulk remaining invisible. And if primordial black holes are grouped in clusters, this arrangement suggests a probability of less than one in 1,000 that a cluster would happen to be along the line of sight of the stars in the nearby satellite galaxies monitored for microlensing events.

To avoid this effect, one could search for microlensing events elsewhere in the sky, looking for the magnified light from stars in the Milky Way's neighboring Andromeda galaxy or even from quasars in far-distant galaxies. In this way, one could probe a much larger volume of galactic halos for signs of MACHOs—that is, for primordial black holes. Recent observations suggest that whereas MACHOs of up to 10 solar masses may not make up the entirety of an average galaxy's halo, MACHOs between one tenth and a few solar masses could easily account for about 20 percent of the mass in a typical galactic

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halo. This value is consistent with our broad-mass primordial black hole scenario.

Simply put, we cannot yet rule out the possibility that dark matter is mostly made up of primordial black holes. Indeed, this proposed scenario could help us decipher several other cosmic mysteries related to dark matter and galaxy formation.

MANY PROBLEMS, ONE SOLUTION

CLUSTERS OF PRIMORDIAL BLACK HOLES could clear up the so-called missing-satellite problem—the apparent lack of "dwarf" satellite galaxies that should form around massive galaxies such as our Milky Way. Current simulations modeling the cosmic distribution of dark matter accurately replicate the universe's observed large-scale structure, in which halos of dark matter pull galaxy clusters into giant filaments and sheets surrounding great voids of lower density. On smaller scales, however, these simulations predict the existence of numerous subhalos of dark matter orbiting around massive galaxies. Each of these subhalos should host a dwarf galaxy, and hundreds should surround the Milky Way. Yet astronomers have found far fewer dwarf galaxies than predicted.

Many potential explanations for the missing-satellite problem exist, mainly the notion that simulations fail to fully account for the influence of ordinary matter (hydrogen and helium in stars) on the formation and behavior of the predicted dwarf galaxies. Our scenario suggests that if clustered primordial black holes made up most dark matter, they would dominate the subhalos surrounding the Milky Way, absorbing a fraction of ordinary matter and reducing the rate of star formation in the subhalos. Moreover, even if these subhalos vigorously formed stars, these stars could easily be ejected by close encounters with massive primordial black holes. Both effects would greatly reduce the brightness of the satellites, making them very hard to detect without wide-field cameras of exquisite sensitivity. Fortunately, such cameras now exist, and astronomers have already used them to discover dozens of ultrafaint dwarf galaxies surrounding the Milky Way. These objects appear to host up to hundreds of times more dark matter than luminous stars, and our model predicts that thousands more should orbit our galaxy.

Simulations also predict a population of galaxies intermediate in size between dwarf galaxies and massive galaxies. Such objects are said to be too big to fail because they would be sufficiently large to readily form stars and be easily seen. Still, they have not turned up in astronomers' searches of the Milky Way's vicinity. This too-big-to-fail problem has a solution similar to that of the missing-satellite problem: massive primordial black holes in the cores of intermediate-sized galaxies could eject stars and star-forming gas from these objects, rendering them effectively invisible to most surveys.

Primordial black holes could also resolve the origin of supermassive black holes (SMBHs). These monsters weigh from millions to billions of solar masses and are observed at the centers of quasars and massive galaxies very early in the universe's history. Yet if these SMBHs formed and grew from the gravitational collapse of the universe's first stars, they should not have acquired such gigantic masses in such a relatively short time—less than a billion years after the big bang.

In our scenario, although most primordial black holes have just tens of solar masses, a very small fraction will be far heavier, ranging from hundreds to tens of thousands of solar masses. Born less than a second after the big bang, these monstrous objects would then act as giant seeds for the formation of the first galaxies and quasars, which would rapidly develop SMBHs at their centers. Such seeds could also account for the existence of intermediate-mass black holes possessing 1,000 to a million solar masses observed orbiting SMBHs and at the centers of globular clusters of stars. In short, primordial black holes may be the missing link between conventional stellar-mass black holes and SMBHs. The observational case for this scenario is building rapidly: recent detections of unexpectedly abundant x-ray sources in the early universe are most easily explained by large numbers of primordial black holes producing x-rays as they gorge on gas less than one billion years after the big bang.

SEEING IN THE DARK

EVEN THOUGH massive primordial black holes could solve the mystery of dark matter, as well as many other long-standing problems of cosmology, the game is not yet over. Other models and explanations are still possible, and future observations should allow us to distinguish among the alternatives. Indeed, there already exist seven kinds of observations to test the primordial black hole scenario [*see box on opposite page*]. They include the detection of ultrafaint dwarf galaxies, the influence of massive primordial black holes on the positions of stars in the Milky Way, the mapping of neutral hydrogen during the first epoch of star formation and future observations of distortions in the cosmic microwave background.

Beyond these experiments, we also now possess a completely new tool to unravel the mysteries of the universe in the form of Advanced LIGO and other gravitational-wave detectors. If indeed LIGO has detected merging members of a hidden population of massive primordial black holes, we should expect many more to be detected in coming years. Before the end of the third run, scientists from the Virgo collaboration in Italy and the Advanced LIGO had presented 50 confirmed detections of gravitational waves emitted during the merging of black hole binaries, and many new detections are expected in future runs. These detections suggest that binary black holes are much more frequent than expected and that they are broadly distributed in mass, in agreement with our scenario of massive primordial black holes.

Taken together these new experiments and observations could confirm the existence of primordial black holes and their possible linkage to the universe's missing matter. Soon we may no longer be in the dark about dark matter. SA

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Sébastien Clesse is a cosmologist and an assistant professor at the Free University of Brussels (ULB) in Belgium. His work covers cosmic inflation, modified gravity and primordial black holes. Clesse is an active member of the Euclid mission, the Square Kilometer Array collaboration and the LISA collaboration.

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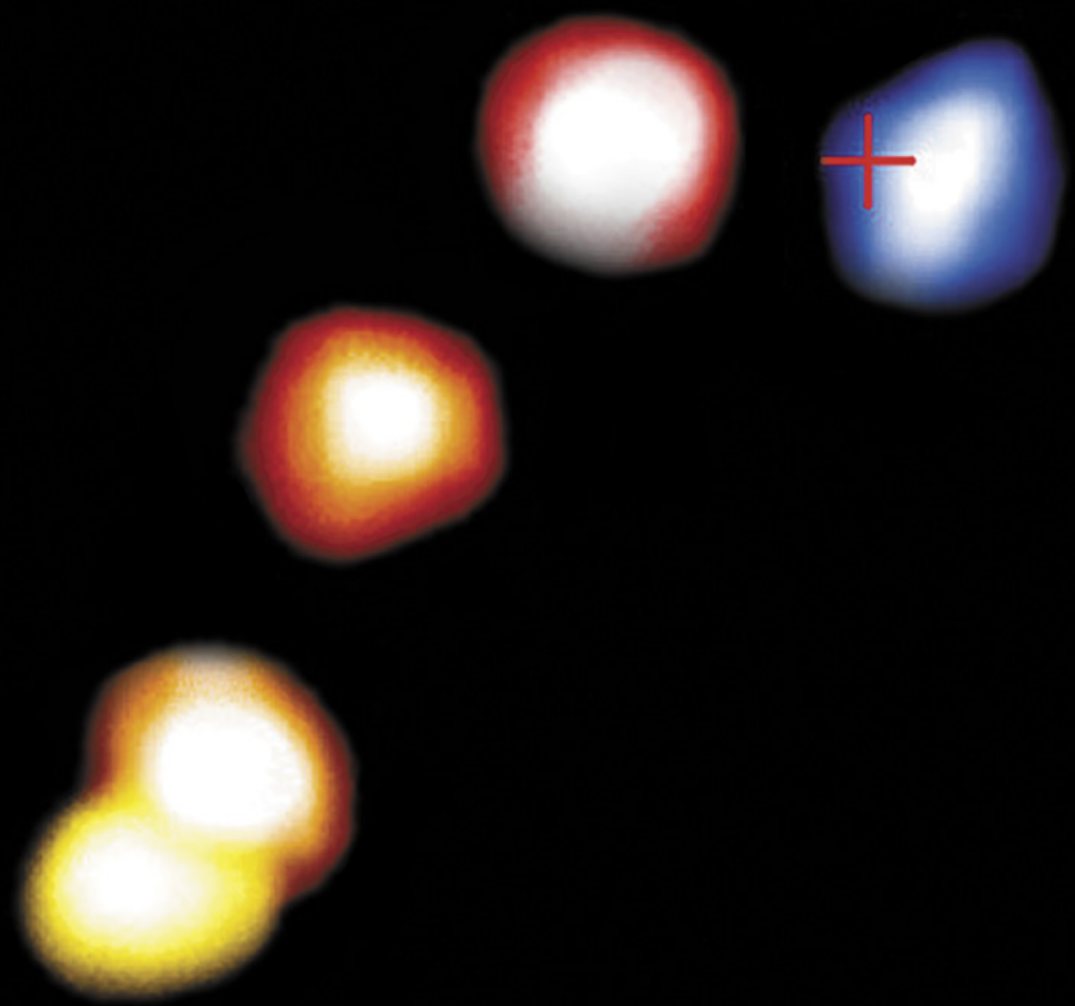

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Milky Way Swarm

Mysterious, dusty objects are swirling around our galaxy's supermassive black hole

By Nadia Drake

COMPOSITE IMAGE shows the motion of the mysterious object G2 as it approached and then passed the supermassive black hole at the Milky Way's core. Astronomers have now discovered several similar objects swirling around the galactic center.

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NEARLY A DECADE AGO AN OBJECT CALLED G2 first enthralled astronomers around the world. G2 was a bizarre hybrid. Containing several Earth masses of material, it looked like a compact mix of gas and dust, yet it moved more like a star, although telescopes could see no signs of starlight seeping out of its interior. The object might have been dismissed as a random astronomical oddity if it did not also happen to be on a path that would bring it dangerously close to the supermassive black hole parked at our galaxy's center.

Astronomers expected that black hole—called Sagittarius A*, or SgrA*—to shred G2 in the summer of 2014, causing a brief blaze of radiation as the ripped-up object fed the black hole's insatiable appetite. But that did not happen: G2 slid right on by SgrA*—scarcely worse for wear, save for some slight deformation of its shape—and continued on its galactic journey.

To this day, astronomers do not agree about what, exactly, G2 is. And a similar SgrA*-orbiting body called G1 is also unexplained. At turns suspected of being compact, gassy clouds or dim stars cloaked by an obscuring shroud, the two objects remain deeply enigmatic.

It turns out that they are not alone. Published in January 2020 in the journal *Nature,* a study reported an additional four so-called G-objects in the Milky Way's center. And just like G1 and G2, they are cosmic chimeras.

"When you have just two of something, it is all mysterious," says Elena Murchikova of the Institute for Advanced Study in Princeton, N.J., who was not involved in the new paper. "This study is a game changer. It triples the number of G-objects and demonstrates that they all are on different orbits, so they are not unique and unlikely results of rare conditions coming together. And they clearly are not a part of the same structure." In other words, the six identified G-objects arose independently, suggesting that whatever cosmic mechanism sculpted them is not rare—and might, in fact, soon be resolved.

G-OBJECTS GALORE

THE STUDY'S lead author, Anna Ciurlo of the University of California, Los Angeles, worked with her colleagues to spot the new objects in 13 years of galactic-center data gathered by an instrument on one of the twin Keck telescopes situated atop Hawaii's dormant volcano Mauna Kea. Initially, she says, she was studying how SgrA* influences the gas near the galactic center.

"But then we kept on finding these very compact objects," she says. "They were not behaving like a gas cloud—they would not get stretched; they would not get eaten by the black hole itself. They were orbiting around the black hole as a star would." In

PRECEDING PAGES: ESO AND A. ECKART

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other words, the newly discerned objects closely resembled the enigmatic G1 and G2.

In the end, Ciurlo flagged four dense, blobby new objects, dubbing them G3 through G6 (although G3 and G6 had been independently detected by other groups). They bring the number of known G-objects to six. Each object is situated within 0.13 light-year of SgrA*. Like G1 and G2, they are all on the order of 100 astronomical units in size (one astronomical unit is roughly the Earth-to-sun distance). But unlike those first two objects, which appear to be on similar orbits, each member of the new quartet traces a wildly divergent path from the others around our galactic nucleus, with orbital periods ranging from 170 to 1,600 years.

"All of this looks very, very believable—there's no doubt of the data," says Stefan Gillessen of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, who discovered G2 and was not involved in the new study. "I really find it is a nice paper."

WHAT ARE THEY?

IN ADDITION to indicating that G-objects are not rare celestial one-offs, the new observations may help solve the fundamental mystery of their origins. Ciurlo and her colleagues think the mysterious hybrids are merged binary stars shrouded in cast-off star stuff. As the team's reasoning goes, most of the stars throughout our galaxy form in pairs, even within the galactic center. But in that chaotic environment, binary stars are not just orbiting each other—they are also being jostled and battered by SgrA*. "The likelihood that these systems would merge is much higher than elsewhere in the galaxy," Ciurlo says.

The resulting merger is likely very messy as each star rips material from the other, eventually expelling about a sun's mass of material to form a gassy, dusty cloud that obscures the newly formed star. "Of course, this needs to be confirmed in the future. But I think it's the most fascinating hypothesis, given what we know about this region," Ciurlo says.

Gillessen, though, is unconvinced that colliding stars are a satisfying explanation for G-objects. Instead he thinks such objects are more likely to be compact gas clouds, perhaps created by a variety of phenomena. "I would be surprised if all of those are of the same category," he says.

Like Ciurlo and her colleagues, Gillessen and his team have studied the galactic center for years, and he does not believe there are sufficient stars in the region to produce mergers often enough for the aftermath of six collisions to be simultaneously visible. "Out of the 40 stars we are seeing [in the galactic center], we have six mergers," he says. "That means that unless these mergers are very long-lived, you immediately start overproducing the number of stars that should be there."

Ciurlo explains that the dusty messiness surrounding a newly merged star could last for a few million years—although she notes that not much is really known about that scenario. And, she observes, the most recent burst of star formation near SgrA* is thought to have occurred between six million and four million years ago. "These types of mergers tend to happen quite early once you form stars," Ciurlo says. "Therefore, we only see the mergers that happened at the beginning, soon after the stellar population formed."

"THIS STUDY IS A GAME CHANGER. IT TRIPLES THE NUMBER OF G-OBJECTS AND DEMONSTRATES THAT THEY ALL ARE ON DIFFERENT ORBITS, SO THEY ARE NOT UNIQUE AND UNLIKELY RESULTS OF RARE CONDITIONS COMING TOGETHER. AND THEY CLEARLY ARE NOT A PART OF THE SAME STRUCTURE."

—ELENA MURCHIKOVA *INSTITUTE FOR ADVANCED STUDY*

PIERCING THE VEIL

ULTIMATELY the G-objects' identities and origins could be unveiled by more detailed observations, made by Keck, instruments on Chile's Very Large Telescope, or future facilities such as the James Webb Space Telescope or the ground-based Thirty Meter Telescope. In the interim, Gillessen says, closely studying G2 over the next few years could be revealing.

Such investigations are promising because stars and gas behave quite differently when they approach a supermassive black hole, and G2's close passage to SgrA* in 2014 could affect the motion of its gassy shroud in a telltale way. Already Gillessen's observations suggest that SgrA* put the brakes on G2, causing the object—or at least its murky exterior—to decelerate. But a dusty, denser star is tougher to slow down. And over time astronomers should perhaps differentiate between emission from the star and its former shroud.

"The gas actually feels different forces than the stellar object, which might reside inside," Gillessen says. "If a few years from now, we see that G2 has separated into a different gaseous and dust component, then the case is clear that there is something inside." SA

Nadia Drake is a science journalist who specializes in covering astronomy, astrophysics and planetary science. Her byline has appeared in *National Geographic*, the *New York Times* and the *Atlantic*, among other publications.

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ARTIST'S RENDITION of two cosmic bodies on the cusp of collision.

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Neutron Star Smashup

The detection of a black hole devouring another cosmic body represents the first of its kind and is opening new vistas on Einstein's general theory of relativity

By Charlie Wood

Illustration by Ron Miller

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SOME 870 MILLION YEARS AGO TWO DEAD STARS became one. Their merger shook the fabric of space with a gravitational wave that swept through Earth on August 14, 2019, rippling through three pairs of carefully calibrated lasers designed to detect their passage. An automated system sent out a preliminary alert 21 seconds later, vibrating smartphones and pinging laptops around the world.

A few years after the Nobel Prize–winning first gravitational-wave detection, which stemmed from a pair of colliding black holes, such alerts had become commonplace. This time, however, astrophysicists instantly knew that the observed event was special. "My jaw dropped when I saw the data," says Geoffrey Lovelace of California State University, Fullerton, a member of the Laser Interferometer Gravitational-wave Observatory (LIGO) Scientific Collaboration.

The wave was detected by LIGO in the U.S. and the Virgo Observatory in Italy at 21:11:18 UTC on August 14, 2019. An automatic first pass pegged it as resulting from an unprecedented merger between a pair of bodies too light to classify, sending astronomers scrambling to look for additional electromagnetic emissions from the event. Subsequent analysis recategorized the signal as a collision between a black hole and a neutron star, a stellar remnant in which gravity squeezes an entire sun's mass into a ball the size of a city. This may be the first such event detected with confidence and, after black hole–black hole mash-ups and mergers between two neutron stars, the third variety of collision detected by gravitational waves. While the classification remains uncertain, this event, now known as GW190814, marks the beginning of a new era of astrophysical studies, with implications for how researchers understand Einstein's general theory of relativity, the deaths of stars and the behavior of extreme matter.

AN "OFF-THE-CHARTS" SIGNAL

CHAD HANNA, a LIGO collaborator and astrophysicist at Pennsylvania State University, was celebrating his wedding anniversary with his wife when his phone went off. His group specializes in rapid classification of LIGO events, so he immediately logged in to check the wave's details. "The first thing I knew was that it was extremely significant," Hanna says, "kind of off-the-charts loud."

The LIGO-Virgo collaboration's algorithmic pipeline spits out a basic classification based on the shape of a wave, its duration and other factors almost instantly—Hanna's team aims for under 20 seconds—so astronomers can immediately slew their telescopes in the celestial direction the wave came from.

On that August day, the automatic system confidently declared that at least one of the objects that produced GW190814 fell into the "mass gap," a wasteland, spanning three to five solar masses, seemingly bereft of black holes and neutron stars. All known black holes weigh more than five suns, while all known neutron stars—born from lighter stars that stopped short of becoming black holes—weigh less than three suns. A mass gap detection would have been a first for LIGO-Virgo—one that would have sharpened the theoretical line separating the heaviest neutron stars from the lightest black holes—but the preliminary label would not last. "There was a handoff around the globe," says Jocelyn Read, an astrophysicist at C.S.U. Fullerton and a LIGO member, beginning with researchers in the U.S. that afternoon and with calculations continuing in Europe well into the following morning.

American scientists woke up on August 14, 2019, to a new classification. Human analysis had pegged the event as a neutron star–black hole merger with greater than 99 percent confidence. LIGO-Virgo has heard the collisions of more than a dozen black hole pairs, as well as two pairs of neutron stars, but it has

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never conclusively heard the rumbles from a black hole swallowing a neutron star.

"This is something I've waited for for a long time," says James Lattimer, an astronomy professor at Stony Brook University and a pioneering nuclear astrophysicist, who showed that neutron star–black hole mergers can spray heavy elements such as gold and uranium into space in his 1976 thesis.

Researchers detected a similar wave in April 2019, but they were not able to confirm that it came from deep space—the signal associated with that potential event, models suggest, has a 60 percent chance of originating from a terrestrial rumble, and such a spurious detection might be expected about once every 20 months. The August 2019 signal, however, initially appeared so clear that a false alarm would have been a once-in-trillions-of-years event. "When it's more than the age of the universe," Lovelace says, "you know it's the real deal." More comprehensive analyses later pegged a false alarm as a once-in-tens-of-thousands-of-years occurrence.

GW190814's deafening signal, however, does not guarantee that astrophysicists have definitely bagged their first neutron star–black hole collision. While the current label clearly puts the heavier object in black hole territory (more than five suns), it leaves the lighter partner in the murky zone below three solar masses. Further analysis refined this partner's weight to 2.6 solar masses, where its identity could still break either way—toward the universe's heaviest-known neutron star or its lightest-known black hole. Theoretical arguments have led physicists to suspect that a black hole is more likely, but without more data they cannot be sure.

LOOKING FOR LIGHT

VIRGO'S DETECTOR in Italy—along with only one of LIGO's two detectors—recognized the wave initially, but the collaboration was able to manually incorporate data from the second LIGO detector overnight. Triangulating from that third detection allowed researchers to pinpoint the source's location in the sky more precisely than any previous wave so soon after detection. "I opened up [the new] sky map, and I was like, 'Oh, they accidentally updated a blank sky map,'" Read recalls thinking before she noticed the tiny dot marking the wave's origin.

The narrowed location, which amounted to 0.06 percent of the sky's total area, came as a boon to astronomical teams hunting for a flash of gamma rays or visible light that could accompany the death of a neutron star, if that is what the lighter partner was. "In principle, it's a manner of minutes to cover that area," says Marcelle Soares-Santos, a cosmologist at Brandeis University, who coordinated follow-up observations using the Dark Energy Camera on a four-meter telescope in Chile.

The black hole may have shredded the potential neutron star, leaving behind a ring of glittering wreckage that faded as it fell into the hole's waiting maw. Alternatively the black hole could have swallowed the neutron star in one clean gulp, with little left to see. LIGO-Virgo simulations for GW190814 predict the latter scenario, but no one knows for sure what actually transpired. Soares-Santos and other teams ultimately did not spot an accompanying flash, which she says may help refine theories of how this first-of-its-kind event could have played out.

PROBING "NEUTRONIUM"

THEORISTS DREAM OF catching the demise of a neutron star because competing theories describing the innards of the enigmatic objects abound. Nuclear physicists seek a glimpse inside the objects, where matter exists at densities that challenge the present best models. If the pressure dissolves neutrons into a plasma of fundamental particles, for instance, neutron stars of a certain mass should appear smaller than they otherwise would be. Fine features of the detected gravitational wave produced as the star spiraled into the black hole may reveal the star's size and, accordingly, the consistency of the matter that fills it. Similarly, whether astronomers see a flash or not will also set limits on the star's size. Such precise measurements of a neutron star's dimensions are "sort of the holy grail of nuclear physics," says Ben Margalit, a postdoctoral researcher at the University of California, Berkeley, who is not part of the collaboration that observed the event.

"THE FIRST THING I KNEW WAS THAT IT WAS EXTREMELY SIGNIFICANT. KIND OF OFF-THE-CHARTS LOUD."
—CHAD HANNA *PENN STATE UNIVERSITY*

A black hole obliterating a neutron star also represents a new arena for testing general relativity. Applying Einstein's theory of gravity to the smooth fabric of spacetime around black holes is tough enough, Lovelace says. Adding in hot, turbulent magnetized neutron star matter—an exotic substance sometimes called neutronium—elevates the challenge to a messy new level.

Even if this ripple in spacetime doesn't divulge any of nature's secrets, researchers feel confident it is just the first of many to come. "I hope it tells us something about black hole–neutron star [mergers]," Lovelace says. "But if not, it still makes me really optimistic that the gravitational sky is bright." SA

Charlie Wood is a journalist covering discoveries in the physical sciences both on and off the planet. His writing has appeared in *Quanta Magazine*, *Popular Science*, and elsewhere.

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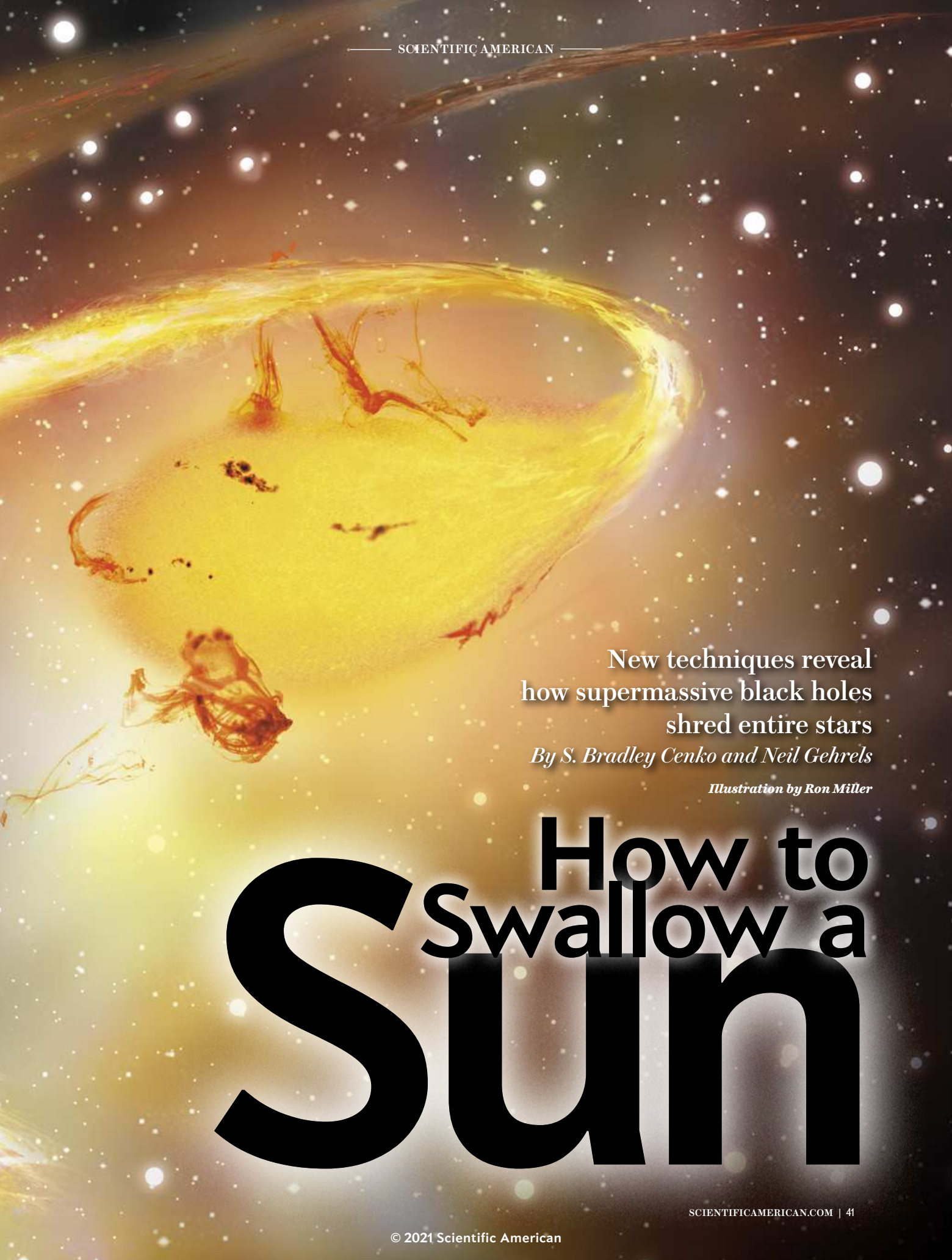

New techniques reveal how supermassive black holes shred entire stars

By S. Bradley Cenko and Neil Gehrels

Illustration by Ron Miller

How to Swallow a Sun

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AT THE HEART OF OUR MILKY WAY AND OF VIRTUALLY EVERY OTHER large galaxy lurks a deep cosmic mystery—a supermassive black hole. Squeezing millions to billions of times more mass than our sun into regions smaller in size than our solar system, these objects are so bizarre as to seem almost mystical. No one yet understands exactly how nature has managed to compress so much matter into such small spaces. What is clear is that the hidden gravitational hands of supermassive black holes reach out to shape their surrounding galaxies in profound yet subtle ways. By studying the growth and behavior of these ghostly black holes, scientists hope to unlock the secrets of how galaxies themselves are born and evolve.

The trouble is that because they emit no light, supermassive black holes spend most of their time dormant and invisible to us. They come to life only when they feed, but their meals are surprisingly rare—most of the gas, dust and stars swirling around them resides in stable orbits and will never be consumed. Yet they are always hungry, and whenever something sizable does happen to fall in, the resulting feeding frenzies can be seen from far, far away.

For most of the past half a century, scientists have primarily observed just one variety of feasting black holes: quasars. Discovered by astronomer Maarten Schmidt in 1963, quasars are the ultraluminous centers of active galaxies that can be seen all the way to the outskirts of the visible universe, each shining brighter than billions of suns. They are thought to occur when massive clouds of gas and dust plunge onto a supermassive black hole for hundreds of thousands or millions of years, compressing, heating and glowing as they circle the black hole's maw. Quasars, however, are less than ideal objects of study. They are extreme events that are typically quite distant and relatively rare, and they constitute a small portion of any supermassive black hole's lifetime. They thus provide a limited view, leaving astronomers blind to how supermassive black holes more routinely feed and grow in the local universe. Researchers have also studied supermassive black holes by clocking the speeds of stars whizzing around them, but these measures work solely for objects very close to home—in the Milky Way or one of our immediate galactic neighbors—where current telescopes can resolve individual stars. Andrea Ghez and Reinhard Genzel shared part of the 2020 Nobel Prize in Physics for their work on the black hole at the center of our galaxy.

In 1988 astronomer Martin Rees proposed a third way to study supermassive black holes—a method that has recently begun to bear fruit. Instead of watching for the steady glow of quasars or the speeds of orbiting stars, astronomers can look for brief, bright flares of light from a black hole's vicinity. Called tidal disruption events (TDEs), these outbursts occur when a supermassive black hole consumes an unlucky star. Unfolding over months rather than millennia, they allow researchers to track the feeding process from beginning to end and are bright enough to be observed in galaxies both near and far.

HOW TO DESTROY A STAR

A TIDAL DISRUPTION EVENT is far more dramatic than the gentle tides that can wash your beach towels away at the sea-

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COSMIC BEACONS CALLED QUASARS are produced by supermassive black holes feasting on gas (*above*) but are too rare, distant and sluggish to wholly reveal how such giant black holes feed. More nuanced detail can come from watching black holes snack on entire stars.

ILLUSTRATION COURTESY OF NASA AND JPL/CALTECH

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shore, but it is not all that different in principle. Earth's tides are chiefly caused by the gravitational tug of the moon, which pulls more strongly on the side of Earth closest to it. This difference between the moon's gravitational pull on the far and near sides of Earth is called a tidal force. That tidal force raises a bulge, or high tide, both on the moon-facing side of Earth and, somewhat paradoxically, on the opposite face as well, which also creates a corresponding low tide, oriented 90 degrees from the Earth-moon axis. When a star is in the vicinity of a supermassive black hole—perhaps pushed there by the gravitational nudging of another nearby star—the intense tidal forces can rip it to shreds.

The details of the star's demise depend on the sizes of both the infalling star and the supermassive black hole. A small, dense object, such as a white dwarf star, will be far more resilient against tidal forces than a larger, puffier, sunlike star—similar to how a bowling ball would be harder to rip apart than a mass of cotton candy. The very largest supermassive black holes, those containing billions of solar masses, are too big to easily create TDEs—they swallow stars whole before the tidal force becomes large enough to tear the stars apart. The tidal forces around a black hole with millions of solar masses, in contrast, will tear apart most stars that approach within about 50 million kilometers—roughly the distance of Mercury from the sun.

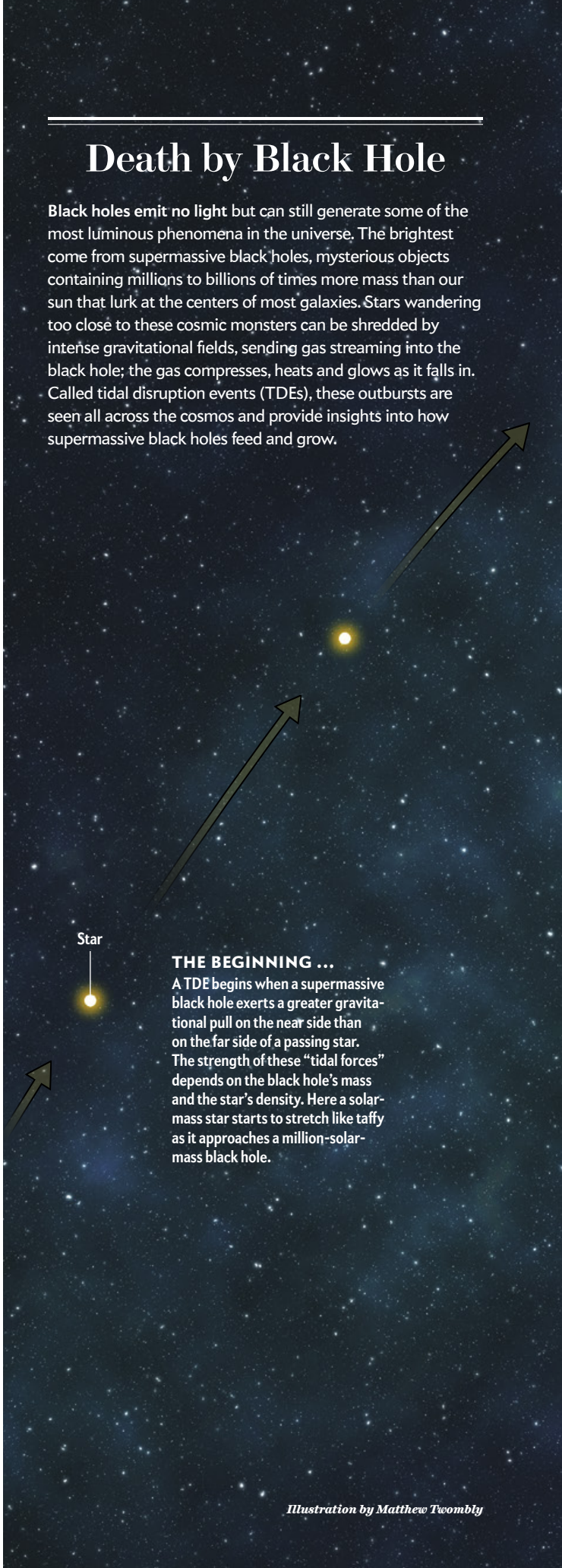
As spectacular as the wholesale disassembly of a star may seem, this is just the beginning of the fireworks display. After the initial disruption, the stellar debris will spread out and gradually diverge from the star's original orbital path. Basic orbital mechanics dictates that roughly half of the debris will be expelled as long filaments of material streaming from the vicinity of the black hole, whereas the other half will loop back around to form an accretion disk—a structure of spiraling rings slowly funneling into the black hole. When the disk's material falls in, it accelerates to nearly the speed of light and glows as gravitational and frictional forces compress and heat it to temperatures approaching 250,000 degrees Celsius. Over a span of weeks or months a typical TDE will cause a previously dormant and invisible black hole to briefly outshine all the stars in its galaxy.

THE FIRST DISCOVERIES

ALTHOUGH THEORISTS first predicted TDEs decades ago, astronomers did not detect any until the 1990s and early 2000s. This delay was in part caused by the rarity of TDEs—they occur once every 100,000 years in a galaxy like the Milky Way, according to estimates. They can also be hard to see. Simple theoretical models suggested that the glow of a TDE's accretion disk should peak in the so-called soft x-ray or far ultraviolet parts of the electromagnetic spectrum—wavelengths that are difficult to access from the ground because of interference from interstellar dust and Earth's atmosphere. Those same models also suggested that astronomers could use a TDE to make relatively precise estimates for the mass of its accompanying black hole—a critical data point for learning exactly how a black hole's size alters its behavior and effects on its galactic surroundings. To measure a black hole's mass, astronomers can simply time how long an accompanying TDE takes to reach peak brightness

Death by Black Hole

Black holes emit no light but can still generate some of the most luminous phenomena in the universe. The brightest come from supermassive black holes, mysterious objects containing millions to billions of times more mass than our sun that lurk at the centers of most galaxies. Stars wandering too close to these cosmic monsters can be shredded by intense gravitational fields, sending gas streaming into the black hole; the gas compresses, heats and glows as it falls in. Called tidal disruption events (TDEs), these outbursts are seen all across the cosmos and provide insights into how supermassive black holes feed and grow.



THE BEGINNING ...
A TDE begins when a supermassive black hole exerts a greater gravitational pull on the near side than on the far side of a passing star. The strength of these "tidal forces" depends on the black hole's mass and the star's density. Here a solar-mass star starts to stretch like taffy as it approaches a million-solar-mass black hole.

Illustration by Matthew Twombly

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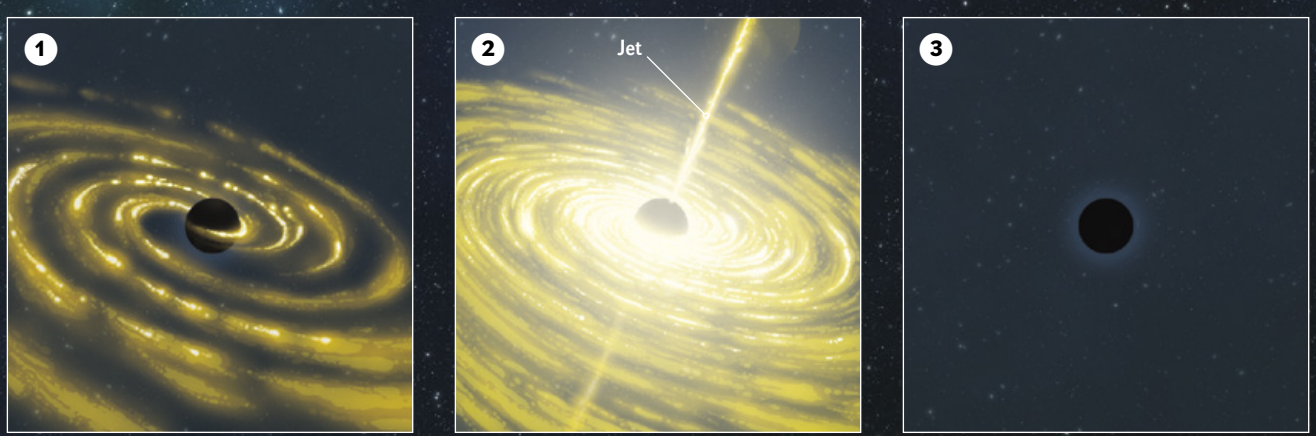
Black hole

... OF THE END

The tidal forces increase as the star gets closer to the black hole, until they overcome the star's self-gravity and rip it apart into arcing filaments of gas. Half the filaments are flung away from the black hole, never to return. The rest swirl into decaying orbits, forming a white-hot accretion disk that funnels the stellar debris into the black hole. Astronomers detect TDEs via the glowing accretion disks left in their wake.

A VIEW LIKE NO OTHER

A TDE is the only known way for astrophysicists to witness a supermassive black hole awaken, feast on a meal and return to quiescence. By tracking how long an accretion disk takes to form (1), reach peak brightness (2) and fade (3), scientists can gauge the size of the consumed star, as well as the black hole's mass and spin. As the black hole feeds, researchers can also monitor shock waves in its accretion disk and the creation of relativistic jets—streams of particles launched at near light speed from a black hole's poles. No other cosmic event offers such detailed views of these extreme, dynamic processes around black holes.



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(which reveals how fast an accretion disk forms and feeds the black hole). Because TDEs are so bright, they allow researchers to pinpoint masses for a wider range of supermassive black holes than any other known phenomenon.

The first TDE candidates were found in data from the ROSAT x-ray and Galaxy Evolution Explorer ultraviolet space telescopes. They appeared as weeks- to months-long flaring events sourced to the centers of previously dormant galaxies. As the first manifestations of this long-predicted phenomenon, these discoveries were especially important for establishing an entirely new field of study. Because they were predominantly found in old data, however, astronomers were unable to study them across multiple wavelengths in real time to unlock their deepest secrets. To catch TDEs as they happened, astronomers would have to be either very lucky or able to continually survey mammoth swaths of sky.

BY STUDYING TIDAL DISRUPTION EVENTS, ASTRONOMERS ARE LEARNING NOT ONLY ABOUT BLACK HOLES BUT ALSO ABOUT STARS BEING RIPPED APART BILLIONS OF LIGHT-YEARS AWAY.

As luck would have it, in the past decade steady progress in data storage and sensors has made such ambitious surveys possible. A high-end optical camera can now image one square degree or more of sky in a single snapshot, a situation akin to suddenly seeing the heavens with a panoramic lens after years of studying them by looking through a straw. By repeatedly surveying large areas of the sky and digitally combining the resulting images to tease out faint, temporary features, astronomers are now able to more easily discover and study TDEs and a host of other transient astrophysical phenomena. These new wide-field surveys, with names such as the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), the Zwicky Transient Facility (ZTF) and the All-Sky Automated Survey for Supernovae (ASAS-SN), were designed largely to identify supernovae and asteroids, but they can do much more. Because they can image millions of galaxies every night, they are also sensitive to more exotic transients such as TDEs.

NEW QUESTIONS FOR A NEW ERA

IN 2010, SHORTLY AFTER Pan-STARRS's on-sky debut, a team led by astronomer Suvi Gezari discovered a TDE called PS1-10jh, which took place around a black hole of perhaps two million solar masses in a galaxy some 2.7 billion light-years from Earth. Because this TDE was noticed soon after the data were collected, Gezari and her colleagues were, for the first time, able to watch it unfold in subsequent optical and ultraviolet observations. What they found was shocking.

Based on careful measurements of its spectrum, this particular TDE appeared to be much too cold. At about 30,000 degrees C, it was more than eight times cooler than predicted by most basic theories of accretion disks. Moreover, rather than fading over weeks as its accretion disk cooled and dissipated, PS1-10jh maintained a constant temperature for many months after the initial discovery. Strangest of all, Pan-STARRS had detected signs of ionized helium in the afterglow—something that could be produced only by temperatures in excess of 100,000 degrees C. And although the TDE appeared to be helium-rich, it also seemed to be devoid of hydrogen, the most abundant element in the universe and the main ingredient of stars. Theorists got to work examining what could produce such confounding results.

To explain PS1-10jh's lack of hydrogen, the Pan-STARRS team suggested that the disrupted star had lost its thick envelope of hydrogen at some point in the past, possibly in a previous interaction with the black hole, leaving only the star's helium-rich core to feed the observed accretion disk. But this alone could not account for the TDE's curious thermal discrepancies—its surprisingly low temperature and, in contradiction, its abundance of helium ionized by much higher temperatures. To solve that mystery, other theorists have postulated that PS1-10jh's black hole–hugging accretion disk was not actually being directly observed. Instead astronomers must have seen a surrounding veil of gas much farther out from the black hole that absorbed the intense radiation produced by the accretion disk and reemitted it at lower temperatures. This veil would have the added bonus of clarifying the apparent absence of hydrogen without the need for an exotic, helium-rich core as the TDE's progenitor. Given the right temperature and a rather high density, such a veil could potentially mask the presence of hydrogen, hiding it in plain sight.

The only trouble was that a thick veil of gas would not be stable at the required distance from the galaxy's central black hole—over time the gas would either fall into the black hole or dissipate to invisibility. The murky origins of this material are still the subject of intense debate and study but, broadly speaking, fall into two possibilities, both related to the dynamics of a feeding black hole. As the remains of a disrupted star loop around a black hole to form a growing accretion disk, shock waves can ripple outward well away from the disk to forestall some of the outlying debris from immediately falling in, creating a temporary screen of material. Alternatively a newborn TDE accretion disk might initially funnel so much material inward that it briefly exceeds a black hole's capacity to feed, forming transient winds or outflows just outside the black hole that push stellar debris out past the accretion disk to much larger distances.

As astronomers sorted through these muddled possibilities for PS1-10jh and other newfound TDEs that soon followed, one thing became perfectly clear: TDEs were a much more complicated phenomenon than anyone had previously appreciated. Yet the biggest surprise was still to come.

A SHOCK FROM SWIFT

IN THE PREDAWN HOURS of March 28, 2011, an automated alert buzzed on the pagers and cell phones of a dedicated team of astronomers around the world. The Swift satellite had just detected a pulse of high-energy radiation from the depths of space. Built by NASA in partnership with research institutions in Italy and the U.K., Swift is an agile space telescope, designed to study all types of exploding objects across the sky. But its main

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targets are gamma-ray bursts, or GRBs—cataclysmic stellar explosions that are the most luminous astrophysical events in the universe. Whenever a torrent of gamma rays trickles into Swift's sensors, the telescope quickly reorients to observe the source in x-rays and optical light and phones home to trigger a complex chain of events on Earth. Within moments of an alert from Swift, astronomers scramble to commandeer the world's largest and most powerful telescopes to look for any emberlike afterglow associated with a GRB before it fades from view forever. Since its launch in 2004, Swift has discovered about 1,400 GRBs, but this particular event, later dubbed Swift J1644+57, proved to be unlike anything the satellite had seen before.

As their name suggests, GRBs tend to be brief, typically lasting anywhere between a fraction of a second and a few minutes. When we turned our telescopes to Swift J1644+57 on that early March morning, we expected to see the standard, fading afterglow of a short-lived GRB. Instead we observed bright, erratic gamma-ray flaring that lasted for a day, followed by months of intense but fading x-ray emissions. Soon we had traced the blast to a galaxy some 3.8 billion light-years away in the constellation of Draco. One of our colleagues, Joshua S. Bloom of the University of California, Berkeley, suggested we had witnessed a TDE and correctly predicted that this particular gamma-ray source would be found at the galaxy's center—the stomping ground of supermassive black holes. But whereas all previous TDEs had been detected at longer, lower-energy wavelengths where observers saw the thermal emission from the accretion disk of a shredded star, this was something wholly different.

How could a TDE produce gamma rays? The best answer we could come up with is that black holes are messy eaters. A black hole would devour most of a disrupted star's gas, locking it away forever behind an event horizon (the boundary past which the black hole's gravitational pull is so great that not even light can escape). But all black holes probably spin, and this spin can push a few percent of the disrupted star's total gas toward the black hole's poles, outside the event horizon, where the gas is accelerated and ejected as collimated beams of particles moving at nearly the speed of light. The fast-moving beams emit gamma rays and x-rays as they hurtle through the cosmos. Apparently Swift had happened to find itself in the path of Swift J1644+57's beam. It was a lucky catch—not all TDEs appear to power such relativistic outflows, and most of those that do likely miss our line of sight.

With the detection of Swift J1644+57 as inspiration, the Swift team began a concerted search for more events. As of early 2021, three more TDEs emitting gamma-ray jets have been found. These rarest and most intense death cries of stars are a novel way to study one of the foremost research topics in modern high-energy astrophysics—the creation and behavior of relativistic particle jets.

THE DEATH OF WORLDS

WHETHER THROUGH the thermal emissions from accretion disks of stellar debris or the gamma rays pouring off a star-devouring black hole's relativistic jets, TDEs offer a new window on the behavior and evolution of supermassive black holes and their surroundings. Most important, unlike the far larger and longer-duration jets and accretion disks of quasars, which are produced by immense clouds of gas chaotically plummeting onto a supermassive black hole across very long timescales, TDEs are brief, clean events that are more easily studied. No human being will ever live long enough to witness the complete life cycle of a single quasar, but already astronomers have found and studied more than 30 TDEs from beginning to end. And in the details of those stellar catastrophes, they have glimpsed tantalizing quirks begging for further study. By precisely measuring the fluctuating flares from TDEs, astronomers are learning not only about black holes but also about the detailed compositions and internal structures of stars being ripped apart billions of light-years away.

They may even eventually learn about a star's companions, too—planets swallowed by black holes. Each flickering flash from a faraway galactic center could signal the deaths of entire worlds. Surveys of stars in our own galaxy have found that almost every one harbors planets; planets probably accompany most, if not all, of the stars in other galaxies as well, including those that suffer TDEs. Even if they were not directly consumed, planets could still find themselves in the path of the transient relativistic jets produced by some TDEs, which extend light-years beyond their black hole sources. Life in any planetary systems unlucky enough to be struck by such a beam would be rapidly extinguished. Someday astronomers may witness a TDE right in our cosmic backyard, when the four-million-solar-mass black hole quiescently lurking at the gas-impoverished center of our very own Milky Way flares to life as it consumes some errant star. It would be very bright but also very safe because we are too far from the galactic center for the TDE's most dangerous effects to reach us here.

The advent of even more powerful surveys heralds a new era of TDE discoveries. The Vera C. Rubin Observatory, an eight-meter telescope currently being constructed in Chile with a field of view covering 10 square degrees of sky, will by itself uncover thousands of these outbursts within a decade of its debut. In some ways, the most challenging aspect of Rubin science will be sifting through the overwhelming number of transient discoveries. Planned radio observatories such as the Square Kilometer Array being built in Australia and South Africa are particularly well suited to identify relativistic jets, even if such jets are "off axis," meaning they are not beamed directly along our line of sight.

In the not too distant future, astronomers may have assembled a TDE catalog with thousands on thousands of entries, more than any individual could study in a lifetime, shedding new light on the masses and behaviors of those elusive hungry ghosts, the otherwise inaccessible supermassive black holes that reside in the hearts of galaxies all across the universe. From that rich, ever growing corpus of knowledge, we can only dream of what further revolutionary discoveries may come. SA

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Neil Gehrels was chief of the Astroparticle Physics Laboratory at NASA's Goddard Space Flight Center, as well as principal investigator of the Swift mission, project scientist for the Wide-Field Infrared Survey Telescope (WFIRST) and deputy project scientist for the Fermi Gamma-ray Space Telescope. He passed away in February 2017.

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WHAT IS SPACETIME?

Physicists believe that at the tiniest scales, space emerges from quanta. What might these building blocks look like?

By George Musser

People have always taken space for granted. It is just emptiness, after all—a backdrop to everything else. Time, likewise, simply ticks on incessantly. But if physicists have learned anything from the long slog to unify their theories, it is that space and time form a system of such staggering complexity that it may defy our most ardent efforts to understand.

Albert Einstein saw what was coming as early as November 1916. A year earlier he had formulated his general theory of relativity, which postulates that gravity is not a force that propagates through space but a feature of spacetime itself. When you throw a ball high into the air, it arcs back to the ground because Earth distorts the spacetime around it, so that the paths of the ball and the ground intersect again. In a letter to a friend, Einstein contemplated the challenge of merging general relativity with his other brainchild, the nascent theory of quantum mechanics. That would not merely distort space but dismantle it. Mathematically, he hardly knew where to begin. "How much have I already plagued myself in this way!" he wrote.

Einstein never got very far. Even today there are almost as many contending ideas for a quantum theory of gravity as scientists working on the topic. The disputes obscure an important truth: the competing approaches all say space is derived from something deeper—an idea that breaks with 2,500 years of scientific and philosophical understanding.

DOWN THE BLACK HOLE

A kitchen magnet neatly demonstrates the problem that physicists face. It can grip a paper clip against the gravity of the entire Earth. Gravity is weaker than magnetism or than electric or nuclear forces. Whatever quantum effects it has are weaker still. The only tangible evidence that these processes occur at all is the mottled pattern of matter in the very early universe—thought to be caused, in part, by quantum fluctuations of the gravitational field.

Black holes are the best test case for quantum gravity. "It's the closest thing we have to experiments," says Ted Jacobson of the University of Maryland, College Park. He and other theorists study black holes as theoretical fulcrums. What happens when you take equations that work perfectly well under laboratory conditions and extrapolate them to the most extreme conceivable situation? Will some subtle flaw manifest itself?

General relativity predicts that matter falling into a black hole becomes compressed without limit as it approaches the center—a mathematical cul-de-sac called a singularity. Theorists cannot extrapolate the trajectory of an object beyond the singularity; its time line ends there. Even to speak of "there" is problematic because the very spacetime that would define the location of the singularity ceases to exist. Researchers hope that quantum theory could focus a microscope on that point and track what becomes of the material that falls in.

Out at the boundary of the hole, matter is not so compressed, gravity is weaker and, by all rights, the known laws of physics should still hold. Thus, it is all the more perplexing that they do not. The black hole is demarcated by an event horizon, a point of no return: matter that falls in cannot get back out. The descent is irreversible. That is a problem because all known laws of fundamental physics, including those of quantum mechanics as generally understood, are reversible. At least in principle, you should be able to reverse the motion of all the particles and recover what you had.

Illustration by Chris Gash

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A very similar conundrum confronted physicists in the late 1800s, when they contemplated the mathematics of a "black body," idealized as a cavity full of electromagnetic radiation. James Clerk Maxwell's theory of electromagnetism predicted that such an object would absorb all the radiation that impinges on it and that it could never come to equilibrium with surrounding matter. "It would absorb an infinite amount of heat from a reservoir maintained at a fixed temperature," explains Rafael Sorkin of the Perimeter Institute for Theoretical Physics in Ontario. In thermal terms, it would effectively have a temperature of absolute zero. This conclusion contradicted observations of real-life black bodies (such as an oven). Following up on work by Max Planck, Einstein showed that a black body can reach thermal equilibrium if radiative energy comes in discrete units, or quanta.

IN PHYSICS AND, MORE GENERALLY, IN THE NATURAL SCIENCES, SPACE AND TIME ARE THE FOUNDATION OF ALL THEORIES. YET WE NEVER SEE SPACETIME DIRECTLY.

Theoretical physicists have been trying for nearly half a century to achieve an equivalent resolution for black holes. The late Stephen Hawking of the University of Cambridge took a huge step in the mid-1970s, when he applied quantum theory to the radiation field around black holes and showed they have a nonzero temperature. As a result, they can not only absorb but also emit energy. Although his analysis brought black holes within the fold of thermodynamics, it deepened the problem of irreversibility. The outgoing radiation emerges from just outside the boundary of the hole and carries no information about the interior. It is random heat energy. If you reversed the process and fed the energy back in, the stuff that had fallen in would not pop out; you would just get more heat. And you cannot imagine that the original stuff is still there, merely trapped inside the hole, because as the hole emits radiation, it shrinks and, according to Hawking's analysis, ultimately disappears.

This problem is called the information paradox because the black hole destroys the information about the infalling particles that would let you rewind their motion. If black hole physics really is reversible, something must carry information back out, and our conception of spacetime may need to change to allow for that.

ATOMS OF SPACETIME

HEAT IS THE RANDOM MOTION of microscopic parts, such as the molecules of a gas. Because black holes can warm up and cool down, it stands to reason that they have parts—or, more generally, a microscopic structure. And because a black hole is just empty space (according to general relativity, infalling matter passes through the horizon but cannot linger), the parts of the black hole must be the parts of space itself. As plain as an expanse of empty space may look, it has enormous latent complexity.

Even theories that set out to preserve a conventional notion of spacetime end up concluding that something lurks behind the featureless facade. For instance, in the late 1970s Steven Weinberg, now at the University of Texas at Austin, sought to describe gravity in much the same way as the other forces of nature. He still found that spacetime is radically modified on its finest scales.

Physicists initially visualized microscopic space as a mosaic of little chunks of space. They thought that if you zoomed in to the Planck scale, an almost inconceivably small size of 10^{-35} meter, you would see something like a chessboard. But that cannot be quite right. For one thing, the grid lines of a chessboard space would privilege some directions over others, creating asymmetries that contradict the special theory of relativity. For example, light of different colors might travel at different speeds—just as in a glass prism, which refracts light into its constituent colors. Whereas effects on small scales are usually hard to see, violations of relativity would actually be fairly obvious.

The thermodynamics of black holes casts further doubt on the picture of space as a simple mosaic. By measuring the thermal behavior of a system, you can count its parts, at least in principle. Dump in energy and watch the thermometer. If the temperature shoots up, that energy must be spread over comparatively few molecules. In effect, you are measuring the entropy of the system, which represents its microscopic complexity.

If you go through this exercise for an ordinary substance, the number of molecules increases with the volume of material. That is as it should be: If you increase the radius of a beach ball by a factor of 10, you will have 1,000 times as many molecules inside it. But if you increase the radius of a black hole by a factor of 10, the inferred number of molecules goes up by only a factor of 100. The number of "molecules" that it is made up of must be proportional not to its volume but to its surface area. The black hole may look three-dimensional, but in fact, it behaves as if it were two-dimensional.

This weird effect goes under the name of the holographic principle because it is reminiscent of a hologram, which presents itself to us as a three-dimensional object. On closer examination, however, it turns out to be an image produced by a two-dimensional sheet of film. If the holographic principle counts the microscopic constituents of space and its contents—as physicists widely, though not universally, accept—it must take more to build space than splicing together little pieces of it.

The relation of part to whole is seldom so straightforward, anyway. An H_2O molecule is not just a little piece of water. Consider what liquid water does: it flows, forms droplets, carries ripples and waves, and freezes and boils. An individual H_2O molecule does none of that: those are collective behaviors. Likewise, the building blocks of space need not be spatial. "The atoms of space are not the smallest portions of space," says Daniele Oriti of Ludwig Maximilian University of Munich in Germany. "They are the constituents of space. The geometric properties of space are new, collective, approximate properties of a system made of many such atoms."

What exactly those building blocks are depends on the theory. In loop quantum gravity, they are quanta of volume aggregated by applying quantum principles. In string theory, they are fields akin to those of electromagnetism that live on the surface traced out by a moving strand or loop of energy—the namesake string. In M-theory, which is related to string theory and may

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underlie it, they are a special type of particle: a membrane shrunk to a point. In causal set theory, they are events related by a web of cause and effect. In the amplituhedron theory and some other approaches, there are no building blocks at all—at least not in any conventional sense.

Although the organizing principles of these theories vary, all strive to uphold some version of the so-called relationalism of 17th- and 18th-century German philosopher Gottfried Leibniz. In broad terms, relationalism holds that space arises from a certain pattern of correlations among objects. In this view, space is a jigsaw puzzle. You start with a big pile of pieces, see how they connect and place them accordingly. If two pieces have similar properties, such as color, they are likely to belong near each other; if they differ strongly, you tentatively put them far apart. Physicists commonly express these relations as a network with a certain pattern of connectivity. The relations are dictated by quantum theory or other principles, and the spatial arrangement follows.

Phase transitions are another common theme. If space is assembled, it might be disassembled, too; then its building blocks could organize into something that looks nothing like space. "Just like you have different phases of matter, like ice, water and water vapor, the atoms of space can also reconfigure themselves in different phases," says Thanu Padmanabhan of the Inter-University Center for Astronomy and Astrophysics in India. In this view, black holes may be places where space melts. Known theories break down, but a more general theory would describe what happens in the new phase. Even when space reaches its end, physics carries on.

ENTANGLED WEBS

THE BIG REALIZATION of recent years—and one that has crossed old disciplinary boundaries—is that the relevant relations involve quantum entanglement. An extrapowerful type of correlation, intrinsic to quantum mechanics, entanglement seems to be more primitive than space. For instance, an experimentalist might create two particles that fly off in opposing directions. If they are entangled, they remain coordinated no matter how far apart they may be.

Traditionally when people talked about "quantum" gravity, they were referring to quantum discreteness, quantum fluctuations and almost every other quantum effect in the book—but never quantum entanglement. That changed when black holes forced the issue. Over the lifetime of a black hole, entangled particles fall in, but after the hole evaporates fully, their partners on the outside are left entangled with—nothing. "Hawking should have called it the entanglement problem," says Samir Mathur of the Ohio State University.

Even in a vacuum, with no particles around, the electromagnetic and other fields are internally entangled. If you measure a field at two different spots, your readings will jiggle in a random but coordinated way. And if you divide a region in two, the pieces will be correlated, with the degree of correlation depending on the only geometric quantity they have in common: the area of their interface. In 1995 Jacobson argued that entanglement provides a link between the presence of matter and the geometry of spacetime—which is to say, it might explain the law of gravity. "More entanglement implies weaker gravity—that is, stiffer spacetime," he says.

Several approaches to quantum gravity—most of all, string theory—now see entanglement as crucial. String theory applies the holographic principle not just to black holes but also to the universe at large, providing a recipe for how to create space—or at least some of it. For instance, a two-dimensional space could be threaded by fields that, when structured in the right way, generate an additional dimension of space. The original two-dimensional space would serve as the boundary of a more expansive realm, known as the bulk space. And entanglement is what knits the bulk space into a contiguous whole.

In 2009 Mark Van Raamsdonk of the University of British Columbia gave an elegant argument for this process. Suppose the fields at the boundary are not entangled—they form a pair of uncorrelated systems. They correspond to two separate universes, with no way to travel between them. When the systems become entangled, it is as if a tunnel, or wormhole, opens up between those universes, and a spaceship can go from one to the other. As the degree of entanglement increases, the wormhole shrinks in length, drawing the universes together until you would not even speak of them as two universes anymore. "The emergence of a big spacetime is directly tied into the entangling of these field theory degrees of freedom," Van Raamsdonk says. When we observe correlations in the electromagnetic and other fields, they are a residue of the entanglement that binds space together.

Many other features of space, besides its contiguity, may also reflect entanglement. Van Raamsdonk and Brian Swingle, now at the University of Maryland, argue that the ubiquity of entanglement explains the universality of gravity—that it affects all objects and cannot be screened out. As for black holes, Leonard Susskind of Stanford University and Juan Maldacena of the Institute for Advanced Study in Princeton, N.J., suggest that entanglement between a black hole and the radiation it has emitted creates a wormhole—a back-door entrance into the hole. That may help preserve information and ensure that black hole physics is reversible.

Whereas these string theory ideas work only for specific geometries and reconstruct only a single dimension of space, some researchers have sought to explain how all of space can emerge from scratch. For instance, ChunJun Cao of the University of Maryland and Spyridon Michalakis and Sean M. Carroll, both at the California Institute of Technology, begin with a minimalist quantum description of a system, formulated with no direct reference to spacetime or even to matter. If it has the right pattern of correlations, the system can be cleaved into component parts that can be identified as different regions of spacetime. In this model, the degree of entanglement defines a notion of spatial distance.

In physics and, more generally, in the natural sciences, space and time are the foundation of all theories. Yet we never see spacetime directly. Rather we infer its existence from our everyday experience. We assume that the most economical account of the phenomena we see is some mechanism that operates within spacetime. But the bottom-line lesson of quantum gravity is that not all phenomena neatly fit within spacetime. Physicists will need to find some new foundational structure, and when they do, they will have completed the revolution that began just more than a century ago with Einstein. SA

George Musser is a contributing editor for *Scientific American*. He is author of *Spooky Action at a Distance* (2015) and *The Complete Idiot's Guide to String Theory* (2008).

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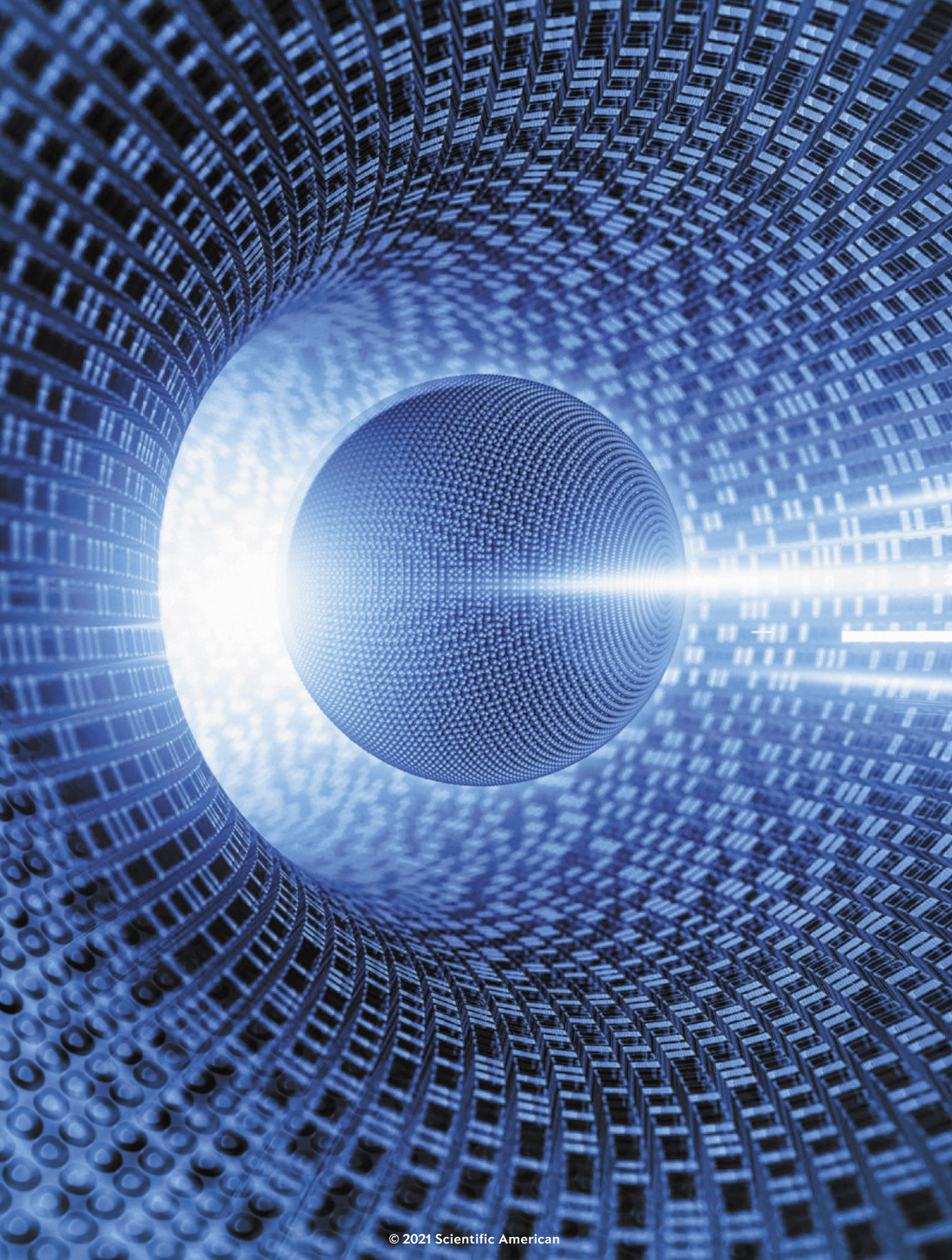

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Tangled Up in Spacetime

The collaborative project "It from Qubit" is investigating whether space and time sprang from the quantum entanglement of tiny bits of information *By Clara Moskowitz*

Illustration by Kenn Brown, Mondolithic Studios

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"All the world's a stage," Shakespeare wrote, and physicists tend to think that way, too. Their stage happens to be space itself, and to them, space sometimes seems like a mere backdrop to the action of the forces and fields that inhabit it. Space, the conventional thinking goes, is not made up of anything at all.

Scientists have begun to question this convention, however. Space—or rather, in the language of general relativity, spacetime—may actually be composed of tiny chunks of information. These chunks, this thinking goes, interact with one another to create spacetime and give rise to its properties, such as the curvature that causes gravity. This notion, if correct, would not just explain spacetime. It could also help physicists achieve a long-sought quantum theory of gravity, which would merge general relativity and quantum mechanics, the two grand theories of the universe that tend not to get along. This line of thinking, dubbed "It from Qubit," has lately intrigued a growing list of physicists.

The "it" in this case is spacetime, and the qubit (pronounced "cue-bit," from "quantum bit") represents the smallest possible amount of information—akin to a computer "bit" but on a quantum scale. The animating idea behind It from Qubit is the notion that the universe is built up from some underlying code and that by cracking this code, physicists will have finally found a way to understand the quantum nature of large-scale events in the cosmos. An early It from Qubit (IfQ) meeting was held in July 2016 at the Perimeter Institute for Theoretical Physics in Ontario. Organizers were expecting about 90 registrants but got so many applications they wound up taking 200 and simultaneously running six remote satellite sessions at other universities. "I think this is one of the most, if not *the* most, promising avenues of research toward pursuing quantum gravity," says Netta Engelhardt, a physics professor at the Massachusetts Institute of Technology, who is not officially involved in It from Qubit but has attended some of its meetings. "It's just taking off."

Because the project involves both the science of quantum computers and the study of spacetime and general relativity, it brings together two groups of researchers who do not usually collaborate—quantum information scientists on one hand and high-energy physicists and string theorists on the other. More than five years ago the Simons Foundation, a private organization that supports science and mathematics research, awarded a grant to found the It from Qubit collaboration and finance physicists to study and hold meetings on the subject. Since then, excitement has grown, and successive meetings have drawn in more and more researchers, some official members of the collaboration funded by Simons and many others simply interested in the topic. "This project is addressing very important questions but very difficult questions," says IfQ collaborator Beni Yoshida, a faculty member at Perimeter. "Collaboration is necessary—it's not like a single person can solve this problem."

Even scientists not working on IfQ have taken notice. "If the link with quantum information theory proves as successful as some anticipate, it could very well spark the next revolution in our understanding of space and time," says string theorist Brian Greene of Columbia University, who is not involved in IfQ. "That's a big deal and hugely exciting."

ENTANGLING SPACETIME

The notion that spacetime has bits or is "made up" of anything is a departure from the traditional picture according to general relativity. The new view holds that spacetime, rather than being fundamental, might "emerge" via the interactions of qubits. What, exactly, are these bits made of, and what kind of information do they contain? Scientists do not know. Yet intriguingly, that does not seem to bother them. "What matters are the relationships" between the bits more than the bits themselves, says IfQ collaborator Brian Swingle, an assistant professor at the University of Maryland, College Park. "These collective relationships are the source of the richness. Here the crucial thing is not the constituents but the way they organize together."

The key to this organization may be the strange phenomenon known as quantum entanglement—a weird kind of correlation that can exist between particles, wherein actions per-

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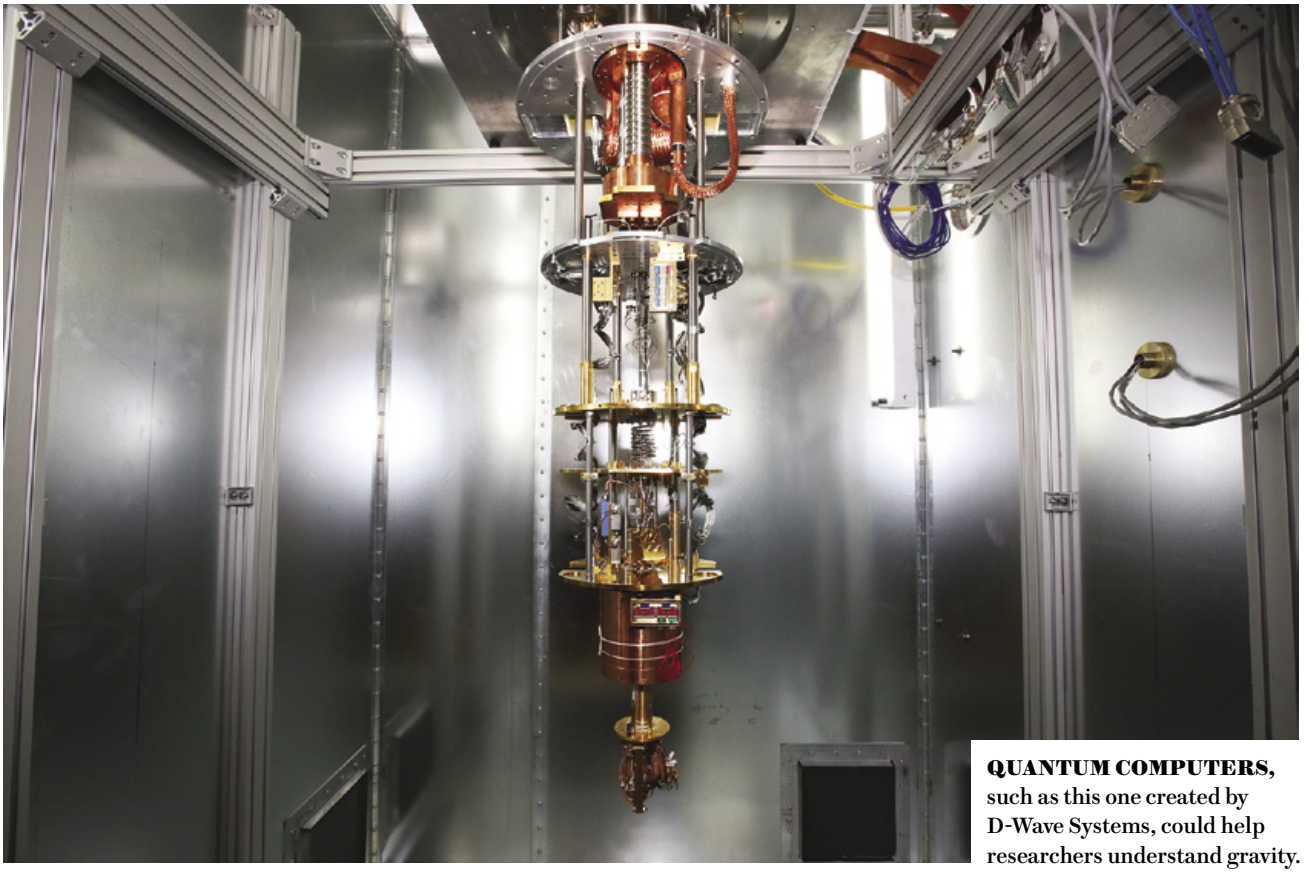

QUANTUM COMPUTERS, such as this one created by D-Wave Systems, could help researchers understand gravity.

KIM STALLKNECHT *New York Times/Redux Pictures*

formed on one particle can affect the other even when a great distance separates them. "Lately one absolutely fascinating proposal is that the fabric of spacetime is knitted together by the quantum entanglement of whatever the underlying 'atoms' of spacetime are," says Vijay Balasubramanian, a physicist at the University of Pennsylvania, who is an IfQ principal investigator. "That's amazing if true."

The reasoning behind the idea comes from several earlier discoveries by physicists, such as a 2006 paper by Shinsei Ryu, now at Princeton University, and Tadashi Takayanagi, now at Kyoto University in Japan, showing a connection between entanglement and the geometry of spacetime. Building on that work, in 2013 physicist Juan Maldacena of the Institute for Advanced Study in Princeton, N.J., and Stanford University physicist Leonard Susskind found that if two black holes became entangled, they would create a wormhole—a shortcut in spacetime predicted by general relativity. This discovery (nicknamed ER=EPR, after physicists' shorthand for wormholes and entanglement, based on the names of the scientists who suggested them) and others like it suggest, surprisingly, that entanglement—which was thought to involve no physical link—can produce structures in spacetime.

To understand how entanglement might give rise to spacetime, physicists first must better understand how entanglement works. The phenomenon has seemed "spooky," in the words of Albert Einstein, ever since he and collaborators predicted it in 1935, because it involves an instantaneous connection between particles at great distances that seems to defy the limitation that nothing can travel faster than the speed of light. Lately scientists have been studying several different kinds of entanglement. Conventional entanglement involves linking a single characteristic (such as a particle's spin) in multiple particles of the same type spread out in space. But "conventional entanglement is not enough," Balasubramanian says. "I've come to realize that there are other forms of entanglement that turn out to be relevant for this project of reconstructing spacetime." One could, for instance, entangle particles of a certain kind at one location with particles of a different kind at the same location—an entanglement that does not involve space. Scientists are also tackling the confusing complexities of entangling larger numbers of particles.

Once the dynamics of entanglement are clearer, scientists hope to comprehend how spacetime emerges, just as the microscopic movements of molecules in the air give rise to the complex patterns of thermodynamics and weather. These are emergent phenomena, Engelhardt says. "When you zoom out of something, you see a different picture that you wouldn't know comes about because of smaller dynamics. This is one of the most fascinating things about It from Qubit because we don't understand the fundamental quantum dynamics from which spacetime emerges."

COSMIC HOLOGRAMS

THE MAJOR GOAL of all this work is to finally achieve a theory that describes gravity from a quantum perspective. Yet physicists chasing this goal have been stymied for the past century—

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Einstein himself pursued such a theory doggedly until his death, with no success. The It from Qubit scientists are banking on an idea known as the holographic principle to help them.

This principle suggests that some physical theories are equivalent to simpler theories that work in a lower-dimensional universe, in the same way that a two-dimensional postcard with a hologram of a unicorn on it can contain all the information necessary to describe and portray the three-dimensional shape of the unicorn. Because finding a working theory of quantum gravity is so hard, this thinking goes, physicists could aim to discover an equivalent, easier-to-work-with theory that operates in a universe with fewer dimensions than ours.

One of the most successful embodiments of the holographic principle is a discovery known as the AdS/CFT correspondence (an acronym for the technical term "anti–de Sitter/conformal field theory correspondence"), which shows one can completely describe a black hole by describing what happens on its surface. In other words, the physics of the inside—the 3-D "bulk"—corresponds perfectly to the physics of the outside—the 2-D "boundary." Maldacena found this relation in the late 1990s, working within the framework of string theory, which is yet another attempt at a theory of quantum gravity. String theory replaces all the fundamental particles of nature with tiny, vibrating strings.

PERHAPS WHAT WE THINK OF AS GRAVITY AND SPACETIME IS JUST ANOTHER WAY OF LOOKING AT THE END PRODUCT OF ENTANGLEMENT.

AdS/CFT might allow physicists to discover a theory that is equivalent to quantum gravity, accomplishes all the same goals and can describe all the same physics but is much easier to work with—by leaving out gravity altogether. "Theories with gravity are very difficult to get quantum descriptions of, whereas theories that don't have gravity are much easier to describe completely," Balasubramanian says. But how, one might ask, could a theory that leaves out gravity ever be a theory of so-called quantum gravity? Perhaps what we think of as gravity and spacetime is just another way of looking at the end product of entanglement—in other words, entanglement might somehow encode the information from the 3-D bulk into bits stored on the 2-D boundary. "It's a very exciting direction," he says.

For about 20 years scientists have found that the AdS/CFT correspondence works—a 2-D theory can describe a 3-D situation, a setup known as a duality—but they do not fully understand why. "We know these two theories are dual, but it's not exactly clear what makes the duality work," Swingle says. "One output [of IfQ] you could hope for is a theory for how these dualities arise. That's something I think definitely can and will happen as a result of this collaboration, or at least [we will make] major progress toward that."

Quantum information theory may be able to help because a concept from this field called quantum error–correcting codes could also be at work in the AdS/CFT correspondence. Scientists researching quantum computing devised these codes to help protect information from being lost if anything interferes with the entanglement between bits. Quantum computers, rather than encoding information in single bits, use highly entangled states of multiple bits. That way a single error cannot affect the accuracy of any piece of information. Strangely, though, the same mathematics involved in quantum error–correcting codes shows up in the AdS/CFT correspondence. It seems that the arrangement that scientists use to entangle multiple bits together into error-proof networks could also be responsible for encoding the information from the interior of the black hole onto its surface through entanglement. "It's very intriguing that you find quantum error–correcting codes inside black holes," says quantum information scientist Dorit Aharonov, an IfQ principal investigator at the Hebrew University of Jerusalem. "Why on earth would that happen? These connections are just fascinating."

Even if physicists manage to understand how the AdS/CFT correspondence works and thereby devise a lower-dimensional theory that stands in for quantum gravity, they are still not home free. The correspondence itself works only in a "toy model" of the universe that is somewhat simplified from the fully realized cosmos we inhabit. In particular, all the rules of gravity that apply in our real universe are not in play in the streamlined world of the correspondence. "AdS/CFT has a kind of gravity, but it's not the theory of gravity in an expanding universe like the one we live in," Swingle says. "It describes a universe as if it was in a bottle—if you shine a light beam, it bounces off the walls of the space. That doesn't happen in our expanding universe." This model gives physicists a useful theoretical playground in which to test their ideas, where the simplified picture makes tackling quantum gravity easier. "You can hope it's a useful way station in the eventual goal of understanding gravity in our own universe," Swingle says.

If IfQ is based on an unrealistic foundation, some skeptics say, how productive can it ever be? "That certainly is one very valid criticism," Engelhardt says. "Why are we focusing on this toy model? All of this depends on the validity of the toy model and the idea that in the end the toy model is representative of our universe. I would like to make sure that if we understand the toy model, we understand the real deal." IfQ researchers are betting that by starting with a simplified picture that is easier to work with, they can eventually add the necessary complexity to apply the theory to the real world.

THE PAYOFF

DESPITE THEIR DOUBTS, scientists inside and outside the project say the approach is worth trying. It has already turned up new avenues of research to pursue. "I've long felt that the relation between quantum information and quantum gravity is

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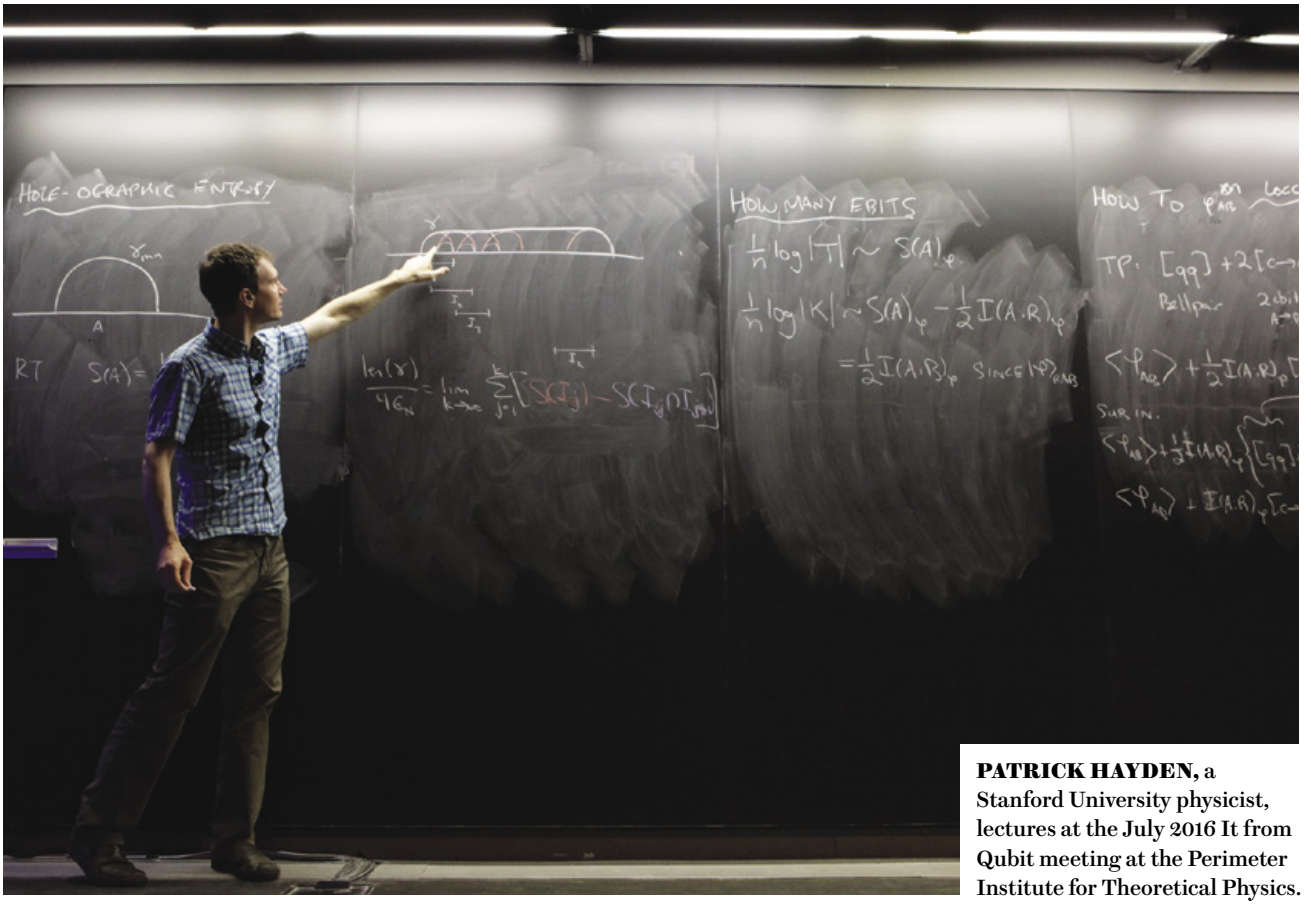

PATRICK HAYDEN, a Stanford University physicist, lectures at the July 2016 It from Qubit meeting at the Perimeter Institute for Theoretical Physics.

COURTESY OF JONGBUM PARK *Perimeter Institute for Theoretical Physics*

of fundamental importance," says Raphael Bousso, a physicist at the University of California, Berkeley, who is not involved in IfQ but has worked with some of its collaborators. "The connection has deepened over the years, and I'm thrilled that so many outstanding scientists are now working together to confront these questions and see where they lead us." Stanford theorist Eva Silverstein, who is not part of the collaboration, concurs: "It is clearly worthwhile to develop and apply quantum information to these problems. But to understand the dynamics [of quantum gravity], much more is required, and it is important for the field not to focus too narrowly on a single approach."

Furthermore, even if the project does not pay off with a theory of quantum gravity, it is still likely to have beneficial offshoots. Bringing the techniques and ideas of string theory and general relativity to bear on questions of quantum information can, for instance, help to better define the different types of entanglement, both for understanding spacetime and for constructing quantum computers. "When you start playing with these tools in a new setting, it's very likely that it will bring up ideas that are interesting and might be useful in other areas," Aharonov says. "It looks like people are making progress on questions that have been out there for many, many years, so it's exciting." Scientists, for instance, have found that measuring time within wormholes may be possible by thinking of the wormhole as a quantum circuit.

Furthermore, combining quantum information science with string theory may help not just in deriving a theory of quantum gravity but also in evaluating whatever theory the researchers may find. Any physical theory can be thought of as a computer, its input and output akin to the theory's initial state and a later state that can be measured—and some computers are more powerful than others. Once researchers have deduced a quantum gravity theory, they could ask, what is the theory's computational power? "If that power is too large, if our quantum gravity model would be able to compute things that we don't believe can be computed in our world, that would at least raise a question mark on the theory," Aharonov says. "It's a way to actually tell whether the theory is sensible or not from a different point of view."

The project reminds some physicists of the heady days in the past when other big ideas were just getting started. "I became a grad student in 1984, when the so-called first string theory revolution took place," says Hirosi Ooguri, a physicist at the California Institute of Technology. "That was a very exciting time, when string theory emerged as a leading candidate for a unified theory of all the forces in nature. I do see the current explosion of excitement around this similarly. This is clearly an exciting time for young people in the field, as well as those of us who received our Ph.D.s decades ago." SA

Clara Moskowitz is *Scientific American*'s senior editor covering space and physics. She has a bachelor's degree in astronomy and physics from Wesleyan University and a graduate degree in science journalism from the University of California, Santa Cruz.

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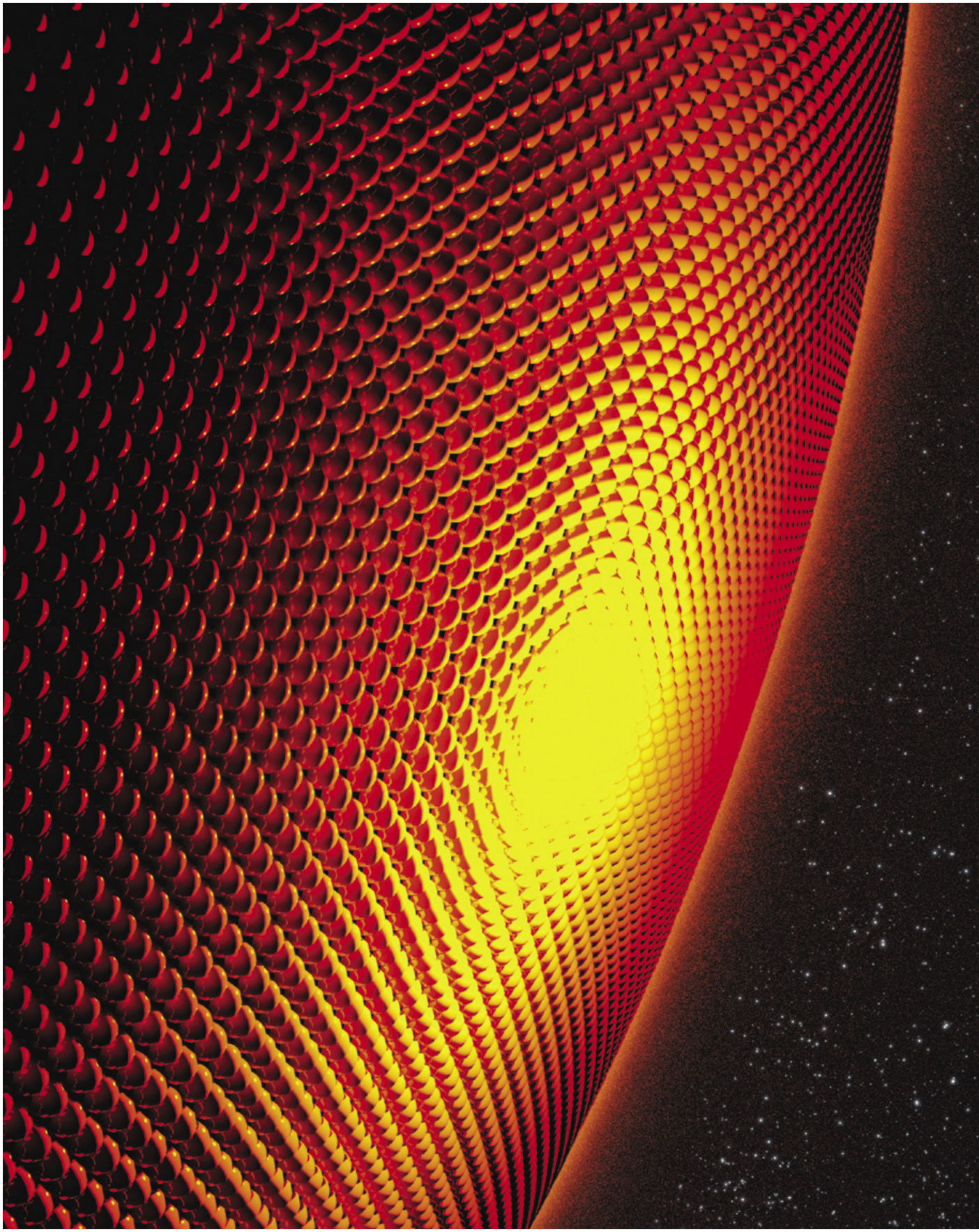

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BURNING RINGS OF FIRE

"Firewalls" of particles may border black holes, confounding both general relativity and quantum mechanics

By Joseph Polchinski

FALLING INTO A BLACK HOLE WAS NEVER GOING TO be fun. As soon as physicists realized that black holes exist, we knew that getting too close to one spelled certain death. But we used to think that an astronaut falling past the point of no return—the so-called event horizon—would not feel anything special. According to Einstein's general theory of relativity, no signposts would mark the spot where the chance of escape dropped to zero. Anyone journeying past the horizon would just seem to fall down, down, down into a pit of blackness.

My colleagues and I have recast that picture in light of some new information about the effects of quantum mechanics on black holes. It now seems that our astronaut would have an experience very different from Albert Einstein's prediction. Rather than falling seamlessly into the interior, the astronaut would encounter a "firewall" of high-energy particles at the horizon that would be instantly lethal. The wall might even mark the end of space.

In 2012 four of us, all then at the University of California, Santa Barbara—my colleague Donald Marolf, then graduate students Ahmed Almheiri and James Sully, and I (now known

Illustration by Kenn Brown, Mondolithic Studios

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by the acronym AMPS)—arrived at this conclusion after using ideas from string theory to take a closer look at the physics of black holes, particularly at an interesting argument put forward in the 1970s by the late Stephen Hawking. Hawking had identified a deep conflict between the predictions of quantum theory and relativity in these extreme environments. According to his reasoning, either quantum mechanics or Einstein's depiction of spacetime is flawed. The battle over which view is correct has swung back and forth ever since.

As with Hawking's original claim, our firewall proposal has raised a storm of disbelief, and no satisfactory alternative has yet emerged. If quantum mechanics is to be trusted, firewalls are the consequence. Yet their existence raises theoretical puzzles as well. It seems that physicists must give up one of our widely cherished beliefs, but we cannot agree on which one. We hope, however, that out of this confusion will come a more complete understanding of quantum mechanics and relativity—and, ideally, a way to finally resolve the apparent contradictions between these two reigning theories of physics.

THE SINGULARITY

GENERAL RELATIVITY, which gave birth to the very concept of black holes, derives its picture of these mysterious entities and their event horizons from an understanding of gravity's effect on space and time. According to the theory, if enough mass comes together, gravity's pull will cause it to start collapsing. Nothing can stop this process until all the mass is compressed into a single point where spacetime is infinitely dense and infinitely curved, called the singularity—in other words, a black hole.

Any space travelers who pass the black hole's event horizon boundary will be unable to escape the gravitational pull and will soon be drawn into the singularity. Even light, once it is past the horizon, cannot escape. The singularity is a very dramatic place, but the horizon itself is supposed to be unremarkable, according to what is called the equivalence principle of general relativity; individuals falling freely into a black hole will see the same physical laws as anywhere else as they cross the horizon. Theorists are fond of saying that the entire solar system could be falling into a giant black hole right now, and we would not experience anything out of the ordinary.

BLACK HOLE RADIATION

THE CHALLENGE HAWKING POSED to the traditional picture of black holes began in 1974, when he considered a strange prediction of quantum mechanics. According to this theory, pairs of particles and their antimatter counterparts constantly pop into existence and then disappear almost at once. If such fluctuations happen just outside the horizon of the black hole, Hawking showed, the pair could separate. One would fall into the singularity, and the other would escape from the black hole and carry away some of its mass. Eventually the black hole's entire mass could be depleted through this process, termed Hawking evaporation.

For black holes found in nature, evaporation is unimportant: these black holes add mass at a much more rapid rate from gas and dust falling in than they lose to radiation. But for theoretical purposes, we can investigate what would happen if a black hole were completely isolated and we had enough time to watch the full process of evaporation. By pursuing such a thought experiment, Hawking revealed two apparent contradictions between general relativity and quantum mechanics.

The entropy problem. In pondering the isolated black hole, Hawking noted that the light spectrum of the eponymous radiation streaming away from it would look the same as that of a radiating hot body, meaning that the black hole has a temperature. In general, temperature arises from the motion of atoms inside objects. The thermal nature of Hawking radiation, then, suggested that the black hole should have a microscopic structure made of some kind of discrete building blocks or bits. The late physicist Jacob D. Bekenstein had also reached this conclusion two years earlier by engaging in thought experiments involving throwing things into black holes. The work of Bekenstein and Hawking gives a formula for the number of bits, a measure known as the black hole entropy. Entropy is a gauge of disorder, which becomes greater as the number of states that an object can have grows. The larger the number of bits in a black hole, the more possible arrangements they can have and the greater the entropy.

In contrast, general relativity describes a black hole as having a smooth geometry and indicates that every black hole of given mass, spin and charge should be exactly the same: in the words of the late physicist John Wheeler of Princeton University, "Black holes have no hair." So here is a contradiction: relativity says no hair, whereas quantum mechanics says black holes have a large amount of entropy, meaning some microscopic structure, or hair.

The information paradox. Hawking evaporation also gives rise to a challenge to quantum theory. According to Hawking's calculation, the particles that escape from a black hole do not depend at all on the properties of the material that went into the hole—usually a massive star that collapsed. For example, we could send a note with a message into the black hole, and there would then be no way to reconstruct the message from the final particles that would emerge. Once the note passed through the horizon, it could not influence anything that came out later, because no information can escape from the interior. In quantum mechanics, every system is described by a formula called the wave function, which encodes the chances that the system will be in any particular state.

In Hawking's thought experiment, the loss of information means that we have no way to predict the wave function of Hawking radiation based on the properties of the mass that went into the black hole. Information loss is forbidden by quantum mechanics, so Hawking concluded that the laws of quantum physics had to be modified to allow for such loss in black holes.

You might be saying to yourself, "Of course, black

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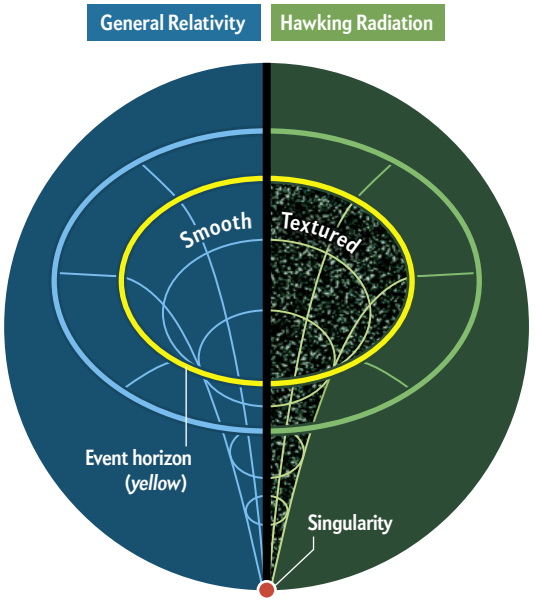
Resolving Black Hole Conundrums

In 1974 Stephen Hawking showed that a small amount of radiation leaks out of black holes. According to quantum mechanics, pairs of particles and their antimatter counterparts constantly spring into existence and then disappear moments later all over the universe. Hawking noted that when a pair shows up near the horizon of a black hole, one particle could fall in while the other escapes. This phenomenon, called Hawking radiation, raises some puzzles about the laws of physics inside black holes.

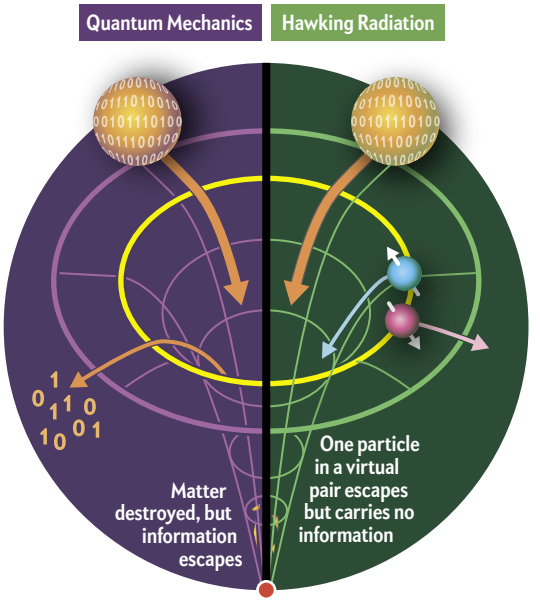
The Entropy Problem

The radiation spectrum of Hawking emission suggests that black holes have temperatures. Traditionally, heat arises from the motion of atoms within an object. The temperature of black holes implies that they have substructure—some type of internal building blocks that can rearrange themselves. The possibility of different arrangements gives black holes a measure of disorder, or "entropy," according to the quantum-mechanical picture of Hawking radiation. Entropy is forbidden to black holes by general relativity, however, because the theory requires them to be completely smooth, without substructure.



The Information Paradox

According to the standard picture of quantum mechanics, information can never be destroyed. Even when you burn a letter, for example, the original information encoded in the atoms of the letter is preserved in the ashes. Hawking radiation, however, implies that black holes destroy the information of the matter that falls into them because the particles that escape do not depend at all on the properties of the atoms that initially fell into the hole. Hawking suggested that quantum mechanics might have to be modified to allow for information loss.


Quantum Mechanics
Hawking Radiation
Matter destroyed, but information escapes
One particle in a virtual pair escapes but carries no information

Earlier Conjectures (*not shown*) …

In an effort to resolve these puzzles, physicists looked for new ways to combine general relativity and quantum mechanics into a coherent theory that could describe black holes. One breakthrough was string theory, which posits that particles are actually tiny loops of vibrating string. This theory appeared to solve elements of the information paradox and the entropy problem.

… Led to Firewalls

Yet the string theory solutions eventually led to a surprising conclusion: black holes might be surrounded by firewalls—walls of high-energy particles that would obliterate any object that encountered them. Firewalls seem to imply a drastic breakdown of the laws of physics at the boundary of black holes and could lead to extreme conclusions, such as the possibility that firewalls mark the end of space and time altogether.

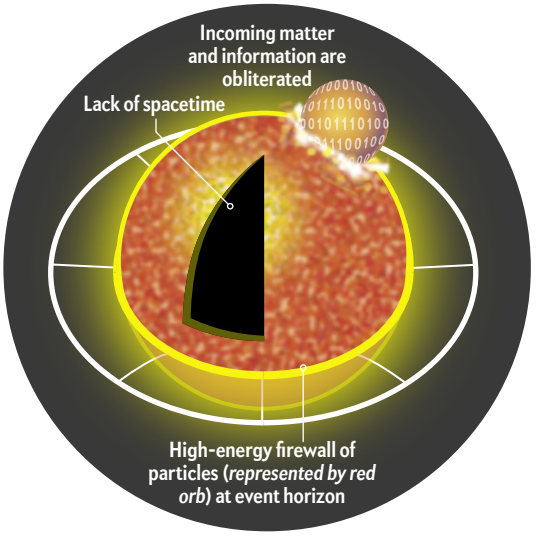

Incoming matter and information are obliterated
Lack of spacetime
High-energy firewall of particles (represented by red orb) at event horizon

Illustration by Jen Christiansen

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holes destroy information—they destroy everything that enters them." But compare what happens if we simply burned the note. The message would certainly be scrambled, and it would be impractical to reconstruct it from the smoke. But the process of burning is described by ordinary quantum mechanics, applied to the atoms in the note, and the quantum description of the smoke would be a definite wave function that would depend on the original message. In theory, then, the message could be reconstructed through the wave function. In the case of black holes, however, there would be no definite wave function for the resulting radiation.

Based on this analogy, many theorists concluded that Hawking was wrong, that he had mistaken the scrambling of information for actual information loss. Further, some argued, if information can be lost, then it will happen not just in the exotic situation of black hole evaporation but everywhere and all the time—in quantum physics, anything that can happen will happen. If Hawking were right, we would see the signs in everyday physics, probably including severe violations of the law of conservation of energy.

Hawking's argument, though, stands up to simple objections. Unlike burning paper, black holes have horizons beyond which information cannot escape. Thus, we seem to have a sharp paradox: either modify quantum mechanics to allow information loss or modify relativity to allow information to escape from the black hole interior.

A third possibility also exists—that the black hole does not evaporate completely but ends up as a microscopic remnant containing all the information of the original star that created it. This "solution" has its own difficulties, however. For example, such a small object containing so much information would violate the Bekenstein-Hawking idea of entropy.

BLACK HOLES AND BRANES

STRING THEORY is one attempt to rectify some of the problems that arise when relativity and quantum mechanics collide, as in the case of black holes. This theory replaces the pointlike particles of previous theories with tiny loops or strands of string; these strings manage to eliminate some of the mathematical difficulties that arise when quantum mechanics and relativity are combined. Replacing points with strings does not, however, immediately change the black hole story.

A break came in 1995, when I was looking at another kind of thought experiment, studying strings in small spaces. Building on work that I and several others had done a few years earlier, I showed that string theory, as it was then understood, was not complete. Rather it required the existence of objects with more dimensions than the three of space and one of time we are familiar with. In black holes these higher-dimensional objects, called D-branes, would be tiny—wrapped up in hidden dimensions too small for us to detect. The next year Andrew Strominger and Cumrun Vafa, both now at Harvard University, showed that strings and D-branes together provide the precise number of bits to account for black hole entropy, at least for certain very symmetrical black holes. The entropy puzzle was partly solved.

The next question was, What about information loss? Then, in 1997, Juan Maldacena, now at the Institute for Advanced Study in Princeton, N.J., came up with a way around the information loss problem—a solution sometimes called the Maldacena duality. A duality is a surprising equivalence between two things that seem very different. Maldacena's duality shows that the mathematics of a theory combining quantum mechanics and gravity—a quantum theory of gravity—based on string theory are equivalent to the mathematics of an ordinary quantum theory under a special set of circumstances. In particular, the quantum physics of a black hole is equivalent to that of an ordinary gas of hot nuclear particles. It also means that spacetime is fundamentally different from what we perceive, more like a three-dimensional hologram projected from a more fundamental two-dimensional surface of a sphere.

Using Maldacena's duality, physicists also get a way to describe the quantum mechanics of black holes in the bargain. If Maldacena's assumptions are true, then ordinary quantum laws apply to gravity as well, and information cannot be lost. By a less direct argument, evaporating black holes cannot leave behind any remnants, so it must be that the information gets out with the Hawking radiation.

Maldacena's duality is arguably the closest we have come to unifying general relativity and quantum mechanics, and Maldacena discovered it by chasing down the black hole puzzles of entropy and information loss. It is not yet proved to be true, but it is supported by much evidence—enough that in 2004 Hawking announced that he had changed his mind about the need for black holes to lose information and publicly paid off a bet with physicist John Preskill at the International Conference on General Relativity and Gravitation in Dublin.

Physicists widely believed that no single observer would see any violation of relativity or any other laws near a black hole that lived by Maldacena's rules, although his duality falls short in not giving a clear explanation for how information gets from the inside of a black hole to the outside.

About 30 years ago Leonard Susskind of Stanford University and Gerard 't Hooft of Utrecht University in the Netherlands proposed a solution to the original information problem that involves a kind of relativity principle called black hole complementarity. In essence, the argument holds that an observer who jumps into a black hole sees the information inside, whereas one who stays outside sees it come out. There is no contradiction because these two observers cannot communicate.

THE FIREWALL

MALDACENA'S DUALITY and black hole complementarity seemed to dispel all the paradoxes, but many of the details had yet to be filled in. In 2012 my own AMPS collaboration tried to make a model of how the combined picture would work, building on ideas of physicists Samir D. Mathur of the Ohio State University and Steven B. Giddings of U.C. Santa Barbara (and extending, unbe-

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knownst to us, an earlier argument of Samuel Braunstein of the University of York in England). After failing repeatedly to make a successful model, we realized that the problem ran deeper than our mathematical shortcomings and that a contradiction remained.

This contradiction pops up when one considers the phenomenon of quantum entanglement—the most unintuitive part of quantum theory and the one furthest from our experience. If particles were like dice, entangled particles would be two dice that always added to seven: if you roll the dice, and the first comes up as two, then the second will always come up as five, and so on. Similarly, when scientists measure the properties of one entangled particle, the measurement also determines the characteristics of its partner. It is a further consequence of quantum theory that a particle can be fully entangled only with one other: if particle B is entangled with particle A, then it cannot be entangled with particle C. Entanglement is monogamous.

In the case of the black hole, think about a Hawking photon; call it "B," emitted after the black hole is at least halfway evaporated. The Hawking process implies that B is part of a pair; call its partner that falls into the black hole "A." A and B are entangled. Furthermore, the information that originally fell into the black hole has been encoded into all the Hawking radiation particles. Now, if information is not lost, and the outgoing Hawking photon B ends up in a definite quantum state, then B must be entangled with some combination, "C," of the other Hawking particles that already escaped (otherwise, the output would not preserve the information). But then we have a contradiction: polygamy!

The price of saving quantum mechanics, keeping the entanglement between B and C and not having anything else out of the ordinary on the outside of the black hole, is the loss of entanglement between A and B. The Hawking photons A and B began just inside and outside the horizon when they arose as an ephemeral particle-antiparticle pair. In quantum theory, the cost of breaking this entanglement, like the cost of breaking a chemical bond, is energy. Breaking the entanglement for all the Hawking pairs implies that the horizon is a wall of high-energy particles, which we termed a firewall. An infalling astronaut, rather than moving freely through the horizon, encounters something dramatic.

Finding such a large departure from general relativity—a wall of energy in a place where nothing unusual should be happening—was disturbing, but the argument was simple, and we could not find a flaw. In a sense, we had just run Hawking's original argument backward, assuming that information is not lost and seeing where that assumption would lead. We concluded that, rather than the subtle effects of complementarity, there was a drastic breakdown of general relativity. As we began to describe the argument to others, the common reaction was first skepticism and then the same puzzlement that we experienced.

Either these strange firewalls actually exist, or it seems we must again consider letting go of some of the deeply held doctrines of quantum theory. Information may not be destroyed, but perhaps some rewriting of quantum mechanics is in store. Unfortunately, observing real black holes will not decide the issue—any radiation from a firewall would be weakened by the gravitational pull of the black hole, making the firewall very hard to see.

THE END OF SPACE

FURTHERMORE, if the firewall exists, what is it? One idea is that the firewall is simply the end of space. Perhaps the conditions for spacetime to form do not exist inside the black hole. As Marolf once remarked, maybe the interior cannot form because "the black hole's quantum memory is full." If spacetime cannot occur inside, then space ends at the horizon, and an infalling astronaut who hits it dissolves into quantum bits residing on this boundary.

To avoid such bizarre scenarios, physicists have attempted to circumvent the firewall conclusion. One idea is that because Hawking radiation particle B must be entangled with both A and C, then A must be part of C: the photon behind the horizon is somehow the same bit that is encoded in the earlier Hawking radiation, even though they are in very different places. This notion is something like the original idea of black hole complementarity, but to make a concrete model of this scenario, it seems, one ends up modifying quantum mechanics again. The most radical idea, from Maldacena and Susskind, is that every pair of entangled particles is connected by a microscopic spacetime wormhole, so that large regions of spacetime, such as the black hole interior, can be built up from large amounts of entanglement.

Hawking had proposed that general relativity works for black holes but that quantum mechanics breaks down. Maldacena concluded that quantum mechanics is unmodified but that spacetime is holographic. Perhaps the truth is somewhere in the middle.

Many other ideas have been proposed, most of which give up one long-standing principle or another, and there is no consensus as to the right direction to resolve the problems. A common question is, What do firewalls imply for real-life black holes, such as the one in the center of our Milky Way galaxy? It is too early to say.

For now investigators are excited that we have discovered a new contradiction between two of the central theories of physics. Our inability to say definitively whether or not the firewall is real exposes a limitation in our current formulations of quantum gravity, and theoretical physicists are rethinking their basic assumptions about the workings of the universe. Out of this may come a deeper understanding of the nature of space and time and of the principles underlying all the laws of physics. Ultimately, by unraveling the quandaries at the heart of black hole firewalls, we may get the break we need to unify quantum mechanics and general relativity into a single working theory. SA

Joseph Polchinski was a professor of physics at the University of California, Santa Barbara, and a permanent member of the Kavli Institute for Theoretical Physics there. His work was crucial to the fields of string theory and quantum gravity and, of course, the firewall paradox, which he devised with contributors. He passed away in 2018.

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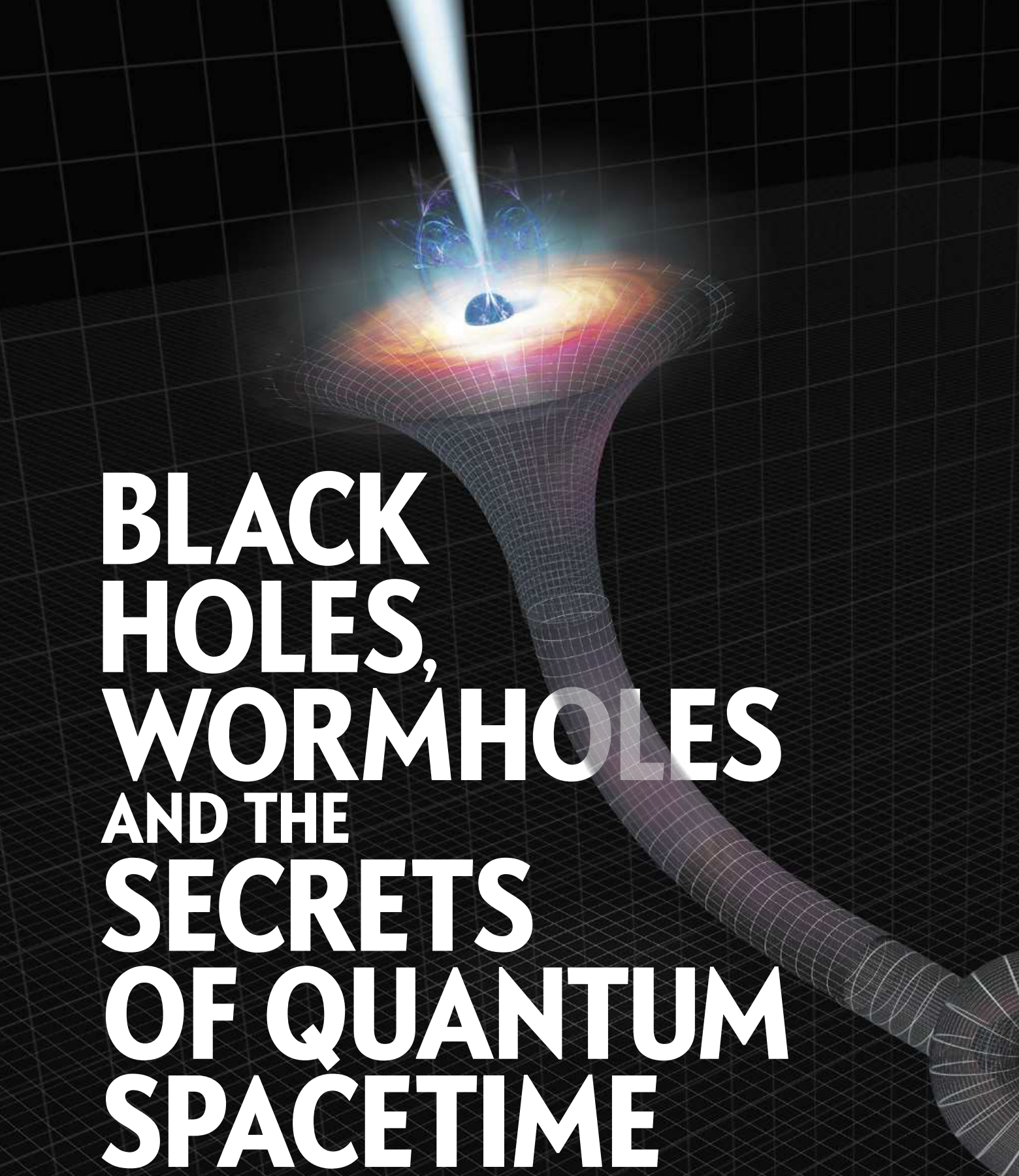

BLACK HOLES, WORMHOLES AND THE SECRETS OF QUANTUM SPACETIME

The weird quantum phenomenon of entanglement could produce shortcuts between distant black holes *By Juan Maldacena*

Illustration by Malcolm Godwin, Moonrunner Design

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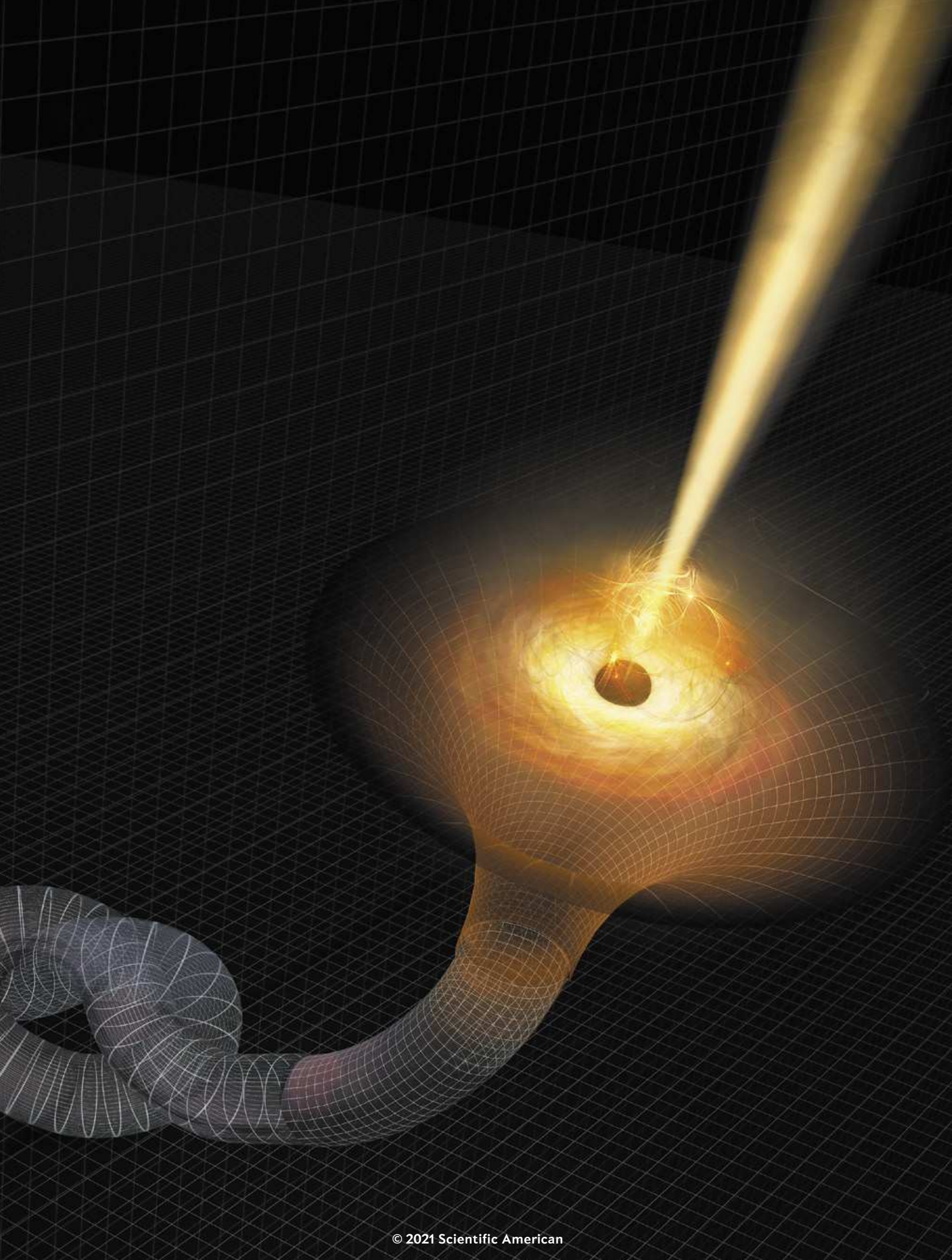

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THEORETICAL PHYSICS IS FULL OF MIND-BOGGLING IDEAS, BUT TWO OF the weirdest are quantum entanglement and wormholes. The first, predicted by the theory of quantum mechanics, describes a surprising type of correlation between objects (typically atoms or subatomic particles) having no apparent physical link. Wormholes, predicted by the general theory of relativity, are shortcuts that connect distant regions of space and time. Work done by several theorists, including myself, has suggested a connection between these two seemingly dissimilar concepts. Based on calculations involving black holes, we realized that quantum mechanics' entanglement and general relativity's wormholes may actually be equivalent—the same phenomena described differently—and we believe the likeness applies to situations beyond black holes.

This equivalence could have profound consequences. It suggests that spacetime itself could emerge from the entanglement of more fundamental microscopic constituents of the universe. It also suggests that entangled objects—despite having long been viewed as having no physical connection to one another—may in fact be connected in ways that are far less fantastical than we thought.

Furthermore, the relation between entanglement and wormholes may help in developing a unified theory of quantum mechanics and spacetime—what physicists call a theory of quantum gravity—that derives the physics of the macroscopic cosmos from the laws that govern the interactions of the atomic and subatomic realms. Such a theory is necessary for understanding the big bang and the interior of black holes.

Interestingly, both quantum entanglement and wormholes date back to two articles written by Albert Einstein and his collaborators in 1935. On the surface, the papers seem to deal with very different phenomena, and Einstein probably never suspected that there could be a connection between them. In fact, entanglement was a property of quantum mechanics that greatly bothered the German-born physicist, who called it "spooky action at a distance." How ironic that it now may offer a bridge to extend his relativity theory to the quantum realm.

BLACK HOLES AND WORMHOLES

TO EXPLAIN WHY I think quantum entanglement and wormholes could be related, we must first describe several properties of black holes, which are intimately involved in this idea. Black holes are regions of curved spacetime that differ drastically from the relatively nondistorted space we are used to. The distinctive feature of a black hole is that we can separate its geometry into two regions: the exterior, where space is curved but objects and messages can still escape, and the interior, lying beyond the point of no return. The interior and exterior are separated by a surface called the event horizon. General relativity tells us that the horizon is just an imaginary surface; an astronaut crossing it would not feel anything special at that location. But having crossed it, a space traveler would be doomed to being squeezed into a region with huge curvature and with no possibility of escape. (In fact, the interior is actually in the future compared with the exterior, so the traveler cannot escape because he or she cannot travel to the past.)

Just a year after Einstein introduced general relativity, German physicist Karl Schwarzschild found the simplest solution to Einstein's equations describing what would later be called black holes. The geometry that Schwarzschild came up with was so unexpected that it took until the 1960s for scientists to fully understand that it describes a wormhole joining two black holes. From the outside the black holes appear to be separate entities sitting at distant locations, yet they share an interior.

In a 1935 paper, Einstein and his colleague Nathan Rosen, then at the Institute for Advanced Study in Princeton, N.J., anticipated that this shared interior was a kind of wormhole (although they did not understand the full geometry it predicted), and for this reason wormholes are also called Einstein-Rosen (ER) bridges.

The wormhole in Schwarzschild's solution differs from black holes that form naturally in the cosmos in that it contains no matter—it is merely curved spacetime. Because of the presence of matter, naturally formed black holes have only one exterior.

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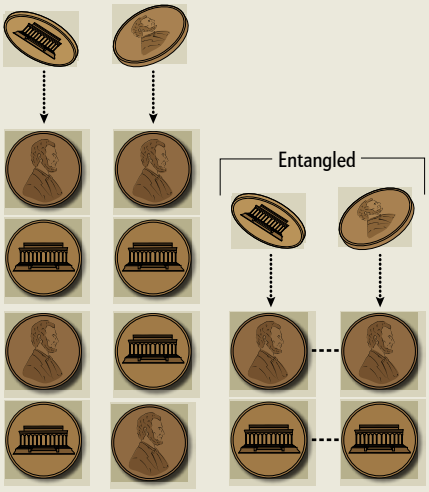
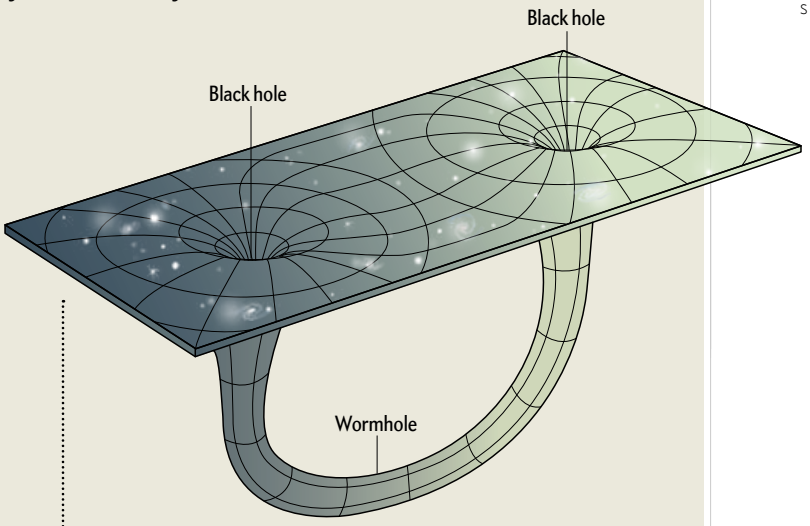
Entanglement Meets Wormholes

Entanglement is a concept from the theory of quantum mechanics describing a special type of correlation between two distant objects. Wormholes, which were predicted by general relativity, are theoretical bridges in spacetime joining distant black holes. Physicists now think that these two phenomena, seemingly disconnected, may be fundamentally related.





ENTANGLEMENT

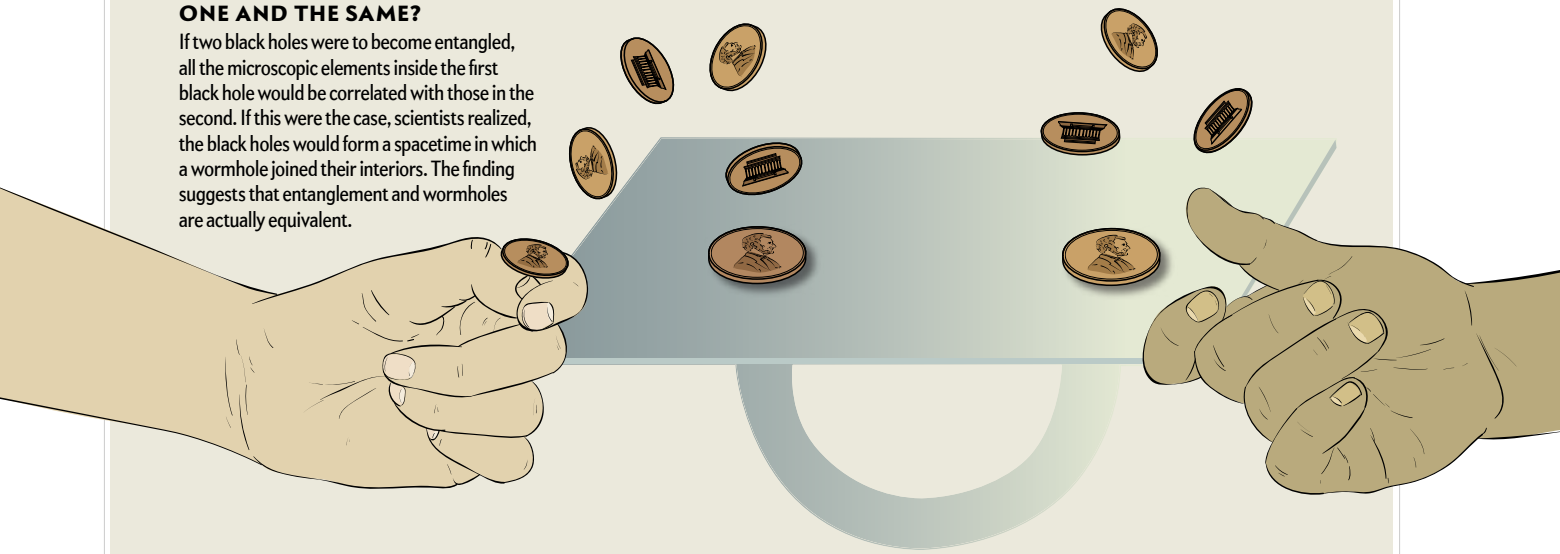
When two normal coins are thrown, the outcome of one has no effect on the other—any two combinations might result. If two coins are entangled, however, then throwing the first coin determines what will happen to the second. If the first comes out heads, for instance, the second must be heads, and if the first is tails, so must the second be.

WORMHOLES

The equations of general relativity suggest that wormholes can connect two black holes, even those located vast distances apart, to create a bridge in spacetime. From the outside the two black holes would appear to be separate entities, but they would share an interior connecting them. No person or signal could travel through, however.

ONE AND THE SAME?

If two black holes were to become entangled, all the microscopic elements inside the first black hole would be correlated with those in the second. If this were the case, scientists realized, the black holes would form a spacetime in which a wormhole joined their interiors. The finding suggests that entanglement and wormholes are actually equivalent.



Most researchers view the full Schwarzschild solution, with its two exteriors, as a mathematical curiosity irrelevant to the black holes in the universe. Nevertheless, it is an interesting solution, and physicists have wondered about its physical interpretation.

The Schwarzschild solution tells us that the wormhole connecting the two black hole exteriors varies with time. It elongates and becomes thinner as time progresses, like a piece of elastic dough being stretched. Meanwhile the two black hole horizons, which at one point touch, separate rapidly. In fact, they pull apart so quickly that we cannot use such a wormhole to travel from one exterior to the other. Alternatively we can say that the bridge collapses before we can cross it. In the dough-

Illustration by Jillian Ditner

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stretching analogy, the collapse of the bridge corresponds to the dough becoming infinitesimally thin as it gets stretched more and more.

It is important to note that the wormholes we are discussing are consistent with the laws of general relativity, which do not allow faster-than-light travel. In that way they differ from science-fiction wormholes that allow instantaneous transport between distant regions of space, as in the 2014 movie *Interstellar*. Science-fiction versions often violate the known laws of physics.

A sci-fi story involving our type of wormhole might look like the following. Imagine two young lovers, Romeo and Juliet. Their families do not like each other and so put Romeo and Juliet in different galaxies, forbidding them to travel. These lovebirds are very smart, however, and manage to construct a wormhole. From the outside the wormhole looks like a pair of black holes, one in Romeo's galaxy and one in Juliet's galaxy. The lovers decide to jump into the interior of their respective black holes. Now, according to their families, they simply committed suicide by jumping in and are never heard from again. Unbeknownst to the outside world, though, the geometry of the wormhole is such that Romeo and Juliet actually meet in the shared interior! And they can live together happily for a while before the bridge collapses, destroying the interior and killing them both.

THE TRADITIONAL WISDOM THAT NOTHING CAN ESCAPE A BLACK HOLE IS TOO SIMPLISTIC.

QUANTUM ENTANGLEMENT

THE 1935 PAPER discussing the other phenomenon of interest to us—entanglement—was written by Einstein, Rosen and Boris Podolsky (also then at the Institute for Advanced Study). The three authors came to be known as EPR. In this famous work, the physicists argued that quantum mechanics allows for the existence of certain strange correlations between distant physical objects, a property that would only later be called entanglement.

Correlations between distant objects can also happen in classical physics. Imagine, for example, that you have a single glove with you because you forgot the other one at home. Before searching your pocket, you do not know whether you have the left or right glove. Once you see that you have the right-hand glove, though, you will immediately know that the one at home is the lefty. But entanglement involves a different kind of correlation, one that exists between quantities governed by quantum mechanics, which are subject to Heisenberg's uncertainty principle. This principle says that there are pairs of physical variables that are impossible to know accurately at the same time. The best-known example involves the position and velocity of a particle: if we measure its position accurately, its velocity becomes uncertain, and vice versa. EPR wondered what would happen if we decided to measure either the positions or the velocities of the individual particles in a pair separated by a wide distance.

The example that EPR analyzed involves two particles with the same mass moving in a single dimension. Let us call these particles R and J because they are the particles that we will imagine being measured by Romeo and Juliet. We can prepare them in such a way that their center of mass has a well-defined position, which we will call x_{cm}, equal to x_R (the position of R) plus x_J (the position of J). We can require the center of mass to equal zero—in other words, we can say that the two particles are always equidistant from the origin. We can also make the particles' relative velocity, v_{rel}, equal to the velocity of R (v_R) minus the velocity of J (v_J), take a precise value; for example, v_{rel} equals some number we can call v_0. In other words, the difference between the two velocities must stay the same. We are here specifying a position and a velocity accurately but not for the same single object, so we do not violate Heisenberg's uncertainty principle. If we have two different particles, nothing prevents us from knowing the position of the first and the velocity of the second. Similarly, once we fix the position of the center of mass, we cannot say anything about the velocity of the center of mass, but we are free to fix the relative velocity.

Here we get to the most amazing part and the thing that makes quantum entanglement seem so strange. Suppose that our particles are far away from each other, and two distant observers, Romeo and Juliet, decide to measure the particles' positions. Now, because of how the particles have been prepared, if Juliet determines any specific value for x_J, then Romeo will find that his particle's position is the negative of Juliet's ($x_R = -x_J$). Note that Juliet's result is random: the position of her particle will vary from measurement to measurement. Romeo's result, however, is completely fixed by Juliet's. Now suppose they both measure their own particle's velocity. If Juliet gets a specific result for v_J, then Romeo will surely find that his velocity is the value of Juliet's plus the relative velocity ($v_R = v_J + v_0$). Again Romeo's result is completely determined by Juliet's. Of course, Romeo and Juliet are free to choose which variable they will measure. In particular, if Juliet measures the position and Romeo measures the velocity, their results will be random and will not display any correlation.

The strange thing is that even though Romeo's measurements of the position and velocity of his particle are constrained by Heisenberg's uncertainty principle, if Juliet decides to measure the position of her particle, Romeo's particle will have a completely certain position once he knows the result of Juliet's measurement. And the same thing will happen with the velocity. It appears as if, when Juliet measured the position, Romeo's particle immediately "knew" that it must have a well-defined position and an uncertain velocity, whereas the opposite should be the case if Juliet measured the velocity. At first glance this situation appears to allow an instantaneous transmission of information: Juliet measures the position, and then Romeo sees a definite position for his particle, thus inferring that Juliet measured the position. Romeo would not be able to realize, however, that his particle has a definite position without knowing the actual value of the position that Juliet mea-

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sured. So in fact, correlations caused by quantum entanglement cannot be used to send signals faster than the speed of light.

Although it has been experimentally confirmed, entanglement may still seem just an esoteric property of quantum systems. Yet during the past two and a half decades these quantum correlations have led to a number of practical applications and breakthroughs in fields such as cryptography and quantum computing.

EQUIVALENCE

HOW MIGHT OUR TWO very different, bizarre phenomena—wormholes and entanglement—be related? A further look at black holes points the way to the answer. The late Stephen Hawking showed in 1974 that quantum effects will cause black holes to emit radiation in the same way a hot object does—proving that the traditional wisdom that nothing can escape a black hole is too simplistic. The fact that black holes radiate implies that they have a temperature—a notion with important ramifications.

Since the 19th century physicists have known that temperature stems from the movement of the microscopic constituents of a system. In a gas, for example, temperature arises from the agitation of molecules. Therefore, if black holes have temperatures, one can expect that they also have some kind of microscopic constituents that collectively are capable of adopting various possible configurations, or so-called microstates. We also believe that, at least as seen from the outside, black holes should behave as quantum systems; that is, they should be subject to all the laws of quantum mechanics. In summary, when we look at a black hole from the exterior, we should find a system that can have many microstates, with the probability of its being in any of these configurations essentially equal for all microstates.

Because black holes look like ordinary quantum systems from the outside, nothing prevents us from considering an entangled pair of them. Imagine a couple of very distant black holes. Each has a large number of possible microscopic quantum states. Now imagine an entangled pair of black holes in which each quantum state in the first black hole is correlated with the corresponding quantum state of the second. In particular, if we measure a certain state for the first hole, the other hole must be in exactly the same state.

The interesting thing is that, based on certain considerations inspired by string theory (one approach toward a theory of quantum gravity), we can argue that a pair of black holes with their microstates entangled in this way (that is, in what might be called an EPR entangled state) would produce a spacetime in which a wormhole (an ER bridge) links the interior of both black holes. In other words, quantum entanglement creates a geometric connection between the two black holes. This result is surprising because entanglement, we thought, involves correlations without a physical connection. But the two distant black holes in this case are physically connected through their interior and brought close via the wormhole.

Leonard Susskind of Stanford University and I have called the equivalence of wormholes and entanglement "ER = EPR" because it relates the two articles that Einstein and his colleagues wrote in 1935. From EPR's point of view, the observations near the horizons of each black hole are correlated because the black holes are in a state of quantum entanglement. From ER's vantage point, the observations are correlated because the two systems are linked through the wormhole.

Now, going back to our Romeo and Juliet sci-fi story, we can see what the lovers should do to form an entangled pair of black holes to produce the wormhole. First they need to create many entangled particle pairs, similar to the ones discussed earlier, with Romeo possessing one member of each entangled pair and Juliet the other. They then need to build very complex quantum computers that will manipulate their respective quantum particles and combine them in a controlled way to create a pair of entangled black holes. Such a feat would be terribly hard to achieve in practice, but it seems possible according to the laws of physics. Besides, we did say Romeo and Juliet were very smart!

A UNIVERSAL PRINCIPLE?

THE IDEAS THAT LED US HERE have been developed over the years by many researchers, beginning with a 1976 article by Werner Israel, then at the University of Alberta. There was also interesting work in 2006 on the connection between entanglement and the geometry of spacetime by Shinsei Ryu and Tadashi Takayanagi, both then at the University of California, Santa Barbara. Susskind and I were motivated by research published in 2012 by Ahmed Almheiri, Donald Marolf, the late Joseph Polchinski and James Sully, all then at U.C. Santa Barbara. They discovered a paradox related to the nature of an entangled black hole's interior. The ER = EPR idea, which says that the interior is part of a wormhole connecting the black hole to another system, alleviates some aspects of this paradox.

Although we identified the connection between wormholes and entangled states using black holes, it is tempting to speculate that the link is more general—that whenever we have entanglement, we have a kind of geometric connection. This expectation should hold true even in the simplest case, in which we have only two entangled particles. In such situations, however, the spatial connection could involve tiny quantum structures that would not follow our usual notion of geometry. We still do not know how to describe these microscopic geometries, but the entanglement of these structures might somehow give rise to spacetime itself. It is as if entanglement can be viewed as a thread connecting two systems. When the amount of entanglement becomes larger, we have lots of threads, and these threads could weave together to form the fabric of spacetime. In this picture, Einstein's relativity equations are governing the connections and reconnections of these threads; quantum mechanics is not just an add-on to gravity—it is the essence of the construction of spacetime.

For now this picture is still wild speculation, but several clues point toward it, and many of us physicists are pursuing its implications. We believe that the seemingly unrelated phenomena of entanglement and wormholes might in fact be equivalent and that this equivalence provides an important clue for developing a description of quantum spacetime—and a long-awaited unification of general relativity and quantum mechanics. SA

Juan Maldacena is a theoretical physicist at the Institute for Advanced Study in Princeton, N.J. He is known for his contributions to the study of quantum gravity and string theory. In 2012 he received a Breakthrough Prize in Fundamental Physics.

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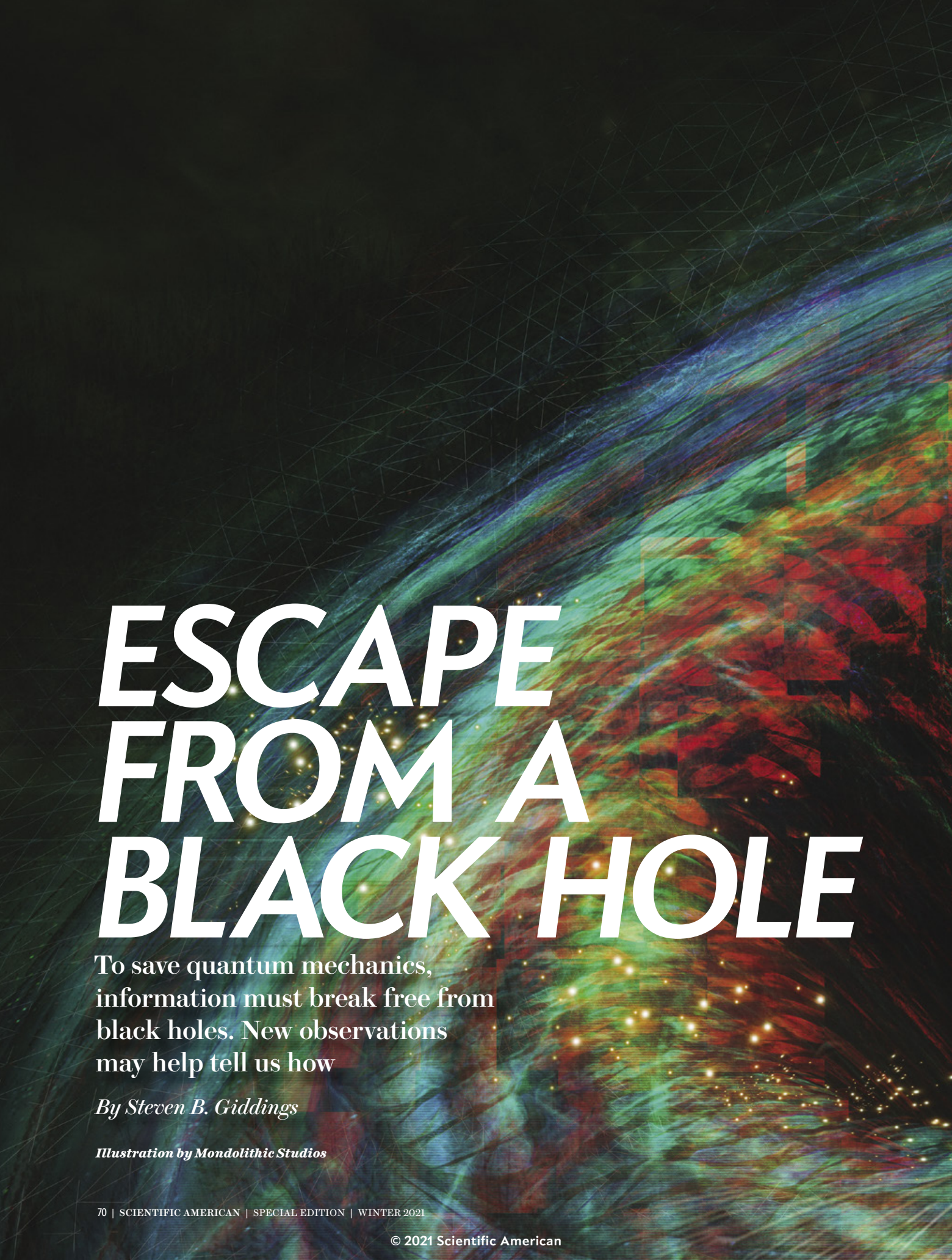

ESCAPE FROM A BLACK HOLE

To save quantum mechanics, information must break free from black holes. New observations may help tell us how

By Steven B. Giddings

Illustration by Mondolithic Studios

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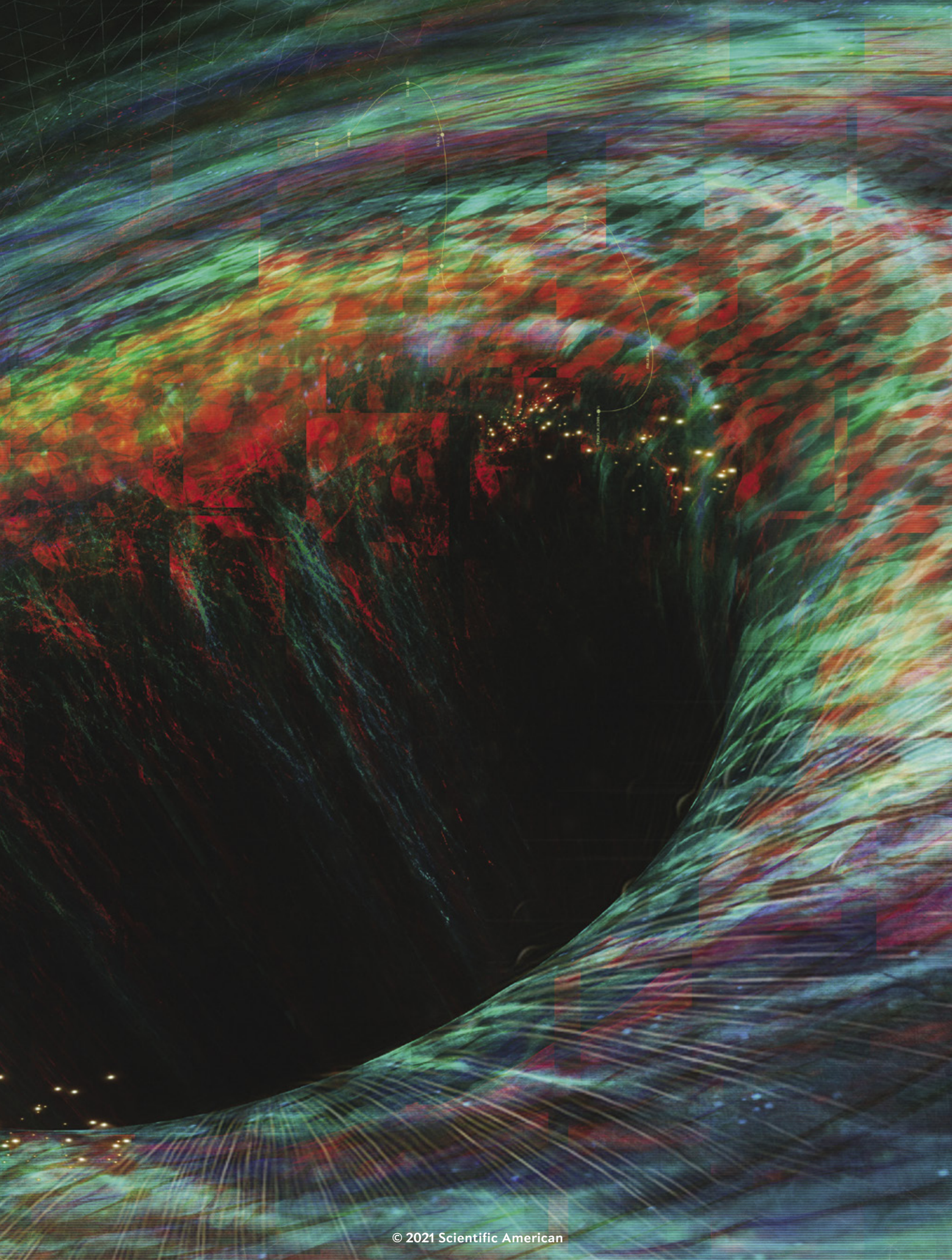

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HUMANKIND CAUGHT ITS FIRST GLIMPSE OF a black hole on April 10, 2019. The Event Horizon Telescope (EHT) team, which uses an Earth-spanning network of radio observatories acting in concert, shared images it had captured of an apparent black hole with 6.5 billion times the mass of our sun in the center of the nearby M87 galaxy. This was a breathtaking achievement—our first view of one of the most mysterious objects in the universe, long predicted but never directly "seen." Even more exciting, the images, and the observations that should follow, are beginning to provide new clues about one of the deepest puzzles in physics.

This enigma is the "paradox" of what happens to information in a black hole. By investigating this question, physicists have discovered that the mere existence of black holes is inconsistent with the quantum-mechanical laws that so far describe everything else in our universe. Resolving this inconsistency may require a conceptual revolution as profound as the overthrow of classical physics by quantum mechanics.

Theorists have explored many ideas, but there has been little direct evidence to help resolve this problem. The first image of a black hole, however, begins to offer actual data to inform our theories. Future EHT observations—especially those that can show how black holes evolve over time—and recent detections of colliding black holes by gravitational-wave observatories could provide important insights and help to usher in a whole new era of physics.

THE INFORMATION PROBLEM

THOUGH DEEPLY MYSTERIOUS, black holes seem to be ubiquitous in the cosmos. The EHT observations and the gravitational-wave measurements are just the latest and most robust evidence that black holes, despite sounding fantastical, do indeed appear to be real—and remarkably common. Yet their very existence threatens the present foundations of physics. The basic principles of quantum mechanics are thought to govern all the other laws of nature, but when they are applied to black holes they lead to a contradiction, exposing a flaw in the current form of these laws.

The problem arises from one of the simplest questions we can ask about black holes: What happens to stuff that falls into them? We need a little refinement here to fully explain. First, according to our present quantum-mechanical laws, matter and energy can shift between different forms: particles can, for example, change into different kinds of particles. But the one thing that is sacred and never destroyed is quantum information. If we know the complete quantum description of a system, we should always be able to exactly determine its earlier or later quantum description with no loss of information. So a more precise question is: What happens to quantum information that falls into a black hole?

Our understanding of black holes comes from Einstein's general theory of relativity, which describes gravity as arising from the curvature of space and time; a common visualization of this idea is a heavy ball deforming the surface of a trampoline. This warping of spacetime causes the trajectories of massive bodies and light to bend, and we call that gravity. If mass is sufficiently concentrated in a small-enough vicinity, the nearby spacetime deformation is so strong that light itself cannot escape a region inside what we call the event horizon: we have a black hole. And if nothing can travel faster than light—including information—everything must get stuck inside this boundary. Black holes become cosmic sinkholes trapping information along with light and matter.

But the story becomes stranger. What may be the late Stephen Hawking's greatest discovery is his 1974 prediction that black holes evaporate. This finding also led to the startling idea that black holes destroy quantum information. According to quantum mechanics, pairs of "virtual particles" pop into existence all the time, everywhere. Typically such a pair, consisting of a particle and its antimatter counterpart, quickly annihilates, but if it forms near the horizon of a black hole, one particle might pop up inside this boundary and the other outside. The outside particle can escape, carrying away energy. The law of

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energy conservation tells us that the black hole has thus lost energy, so the emission of such particles causes the black hole to shrink over time until it completely disappears. The problem is that the escaping particles, known as Hawking radiation, carry essentially no information about what went into the black hole. Therefore, Hawking's calculations appear to show that quantum information that falls into a black hole is ultimately destroyed—contradicting quantum mechanics.

This revelation initiated a deep crisis in physics. Great advances have followed from previous such crises. For instance, at the beginning of the 20th century, classical physics seemed to predict the inevitable instability of atoms, in obvious contradiction to the existence of stable matter. That problem played a key role in the quantum revolution. Classical physics implied that because orbiting electrons within atoms are constantly changing direction, they continually emit light, causing them to lose energy and spiral into the nucleus. But in 1913 Niels Bohr proposed that electrons actually travel only within quantized orbits and cannot spiral in. This radical idea helped to establish the basis of quantum mechanics, which fundamentally rewrote the laws of nature. Increasingly it seems that the black hole crisis will similarly lead to another paradigm shift in physics.

QUANTUM ALTERNATIVES

WHEN HAWKING FIRST predicted black hole evaporation, he suggested that quantum mechanics must be wrong and that information destruction is allowed. Yet physicists soon realized this change would require a drastic breakdown of the law of energy conservation, which would disastrously invalidate our present description of the universe. Apparently the resolution must be sought elsewhere.

Another early idea was that black holes do not completely evaporate but instead stop shrinking at a tiny size, leaving behind microscopic remnants containing the original information. But, scientists realized, if this were true, basic properties of quantum physics would predict catastrophic instabilities causing ordinary matter to explode into such remnants, also contradicting everyday experience.

Obviously something is deeply wrong. It is tempting to conclude that the flaw is in Hawking's original analysis and that somehow information does escape a black hole emitting Hawking radiation. The challenge here is that this scenario would conflict with a foundational concept of present-day physics, the principle of locality, which states that information cannot move from one place to another superluminally—that is, faster than the speed of light. But according to our definition of black holes, the *only* way to escape one is to travel faster than light, so if information does escape, it must be doing so superluminally, in conflict with locality. In the four decades since Hawking's discovery, physicists have tried to

The Information Problem

Black holes were predicted by general relativity, and mounting astrophysical evidence supports their existence. But in 1974 Stephen Hawking argued that black holes eventually evaporate. If so, everything that falls into them is ultimately destroyed, including the information contained in the matter that fell in. The problem is that quantum mechanics and energy conservation forbid such destruction of information. In response, physicists have come up with several suggestions for how to modify our picture of black holes to make them compatible with quantum physics:

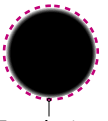
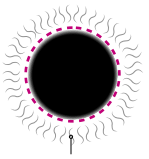
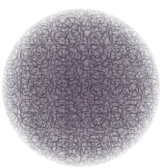
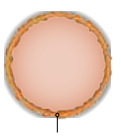
	HYPOTHESIS	DESCRIPTION	PROBLEM
Information is destroyed	**"Classical" black hole** 	Black hole with an event horizon; information that enters the black hole is destroyed when the black hole evaporates.	Contradicts quantum mechanics and energy conservation, which say that information cannot be destroyed.
Information is not destroyed	**Soft hair** 	Information does not fully enter the black hole but instead leaves an "imprint" just outside the event horizon.	Most experts do not regard this picture as providing a convincing resolution.
	Fuzzball 	A type of massive remnant in which the black hole horizon is replaced by strings and higher-dimensional geometry.	All three of these scenarios require modification of the conventional notion of locality—that is, the idea that nothing, including information, can travel faster than light.
	Firewall 	A type of massive remnant in which a "wall" of high-energy particles replaces the horizon; there is no black hole interior.	
	Quantum halo	A quantum black hole interacts with its surroundings, possibly through small fluctuations in spacetime, allowing information to transfer out.	

Illustration by Amanda Montañez

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find a loophole to this argument that stays within conventional physics, but none has emerged.

The closest attempt was a 2016 proposal by Hawking, Malcolm Perry and Andrew Strominger, who suggested that a mistake in the original analysis implies information never fully enters a black hole but instead leaves a kind of imprint in the form of what they called "soft hair" outside it. Closer examination seems to be closing this loophole, however, and most experts do not believe that this can be the answer. In short, more radical steps appear to be needed.

An obvious idea is that there is some unknown physics that prevents true black holes from existing at all. The conventional picture of black hole formation says that when very large stars burn out and die, their mass collapses under the force of gravity into a black hole. But what if they never reach that stage and actually transform into objects with "better" behavior? In fact, we know that when lower-mass stars such as our sun burn out and collapse, they do not form black holes and instead form dense remnants—for example, white dwarfs or neutron stars. Perhaps some unknown laws of physics also prevent larger stars from forming black holes and instead lead them to become a kind of "massive remnant"—something more like a neutron star than a black hole.

The problem with this suggestion is that we cannot explain what would stabilize such objects—no known physics should prevent their continued collapse under gravity, and any imagined physics that did would apparently require superluminal signaling from one side of the collapsing matter to the other. In fact, conventional large black holes can form from *very* low-density matter. To illustrate, if the 6.5-billion-solar-mass black hole in M87 arose from the collapse of a dust cloud (which is theoretically possible, although the actual process was apparently more complex), it would have happened when the dust reached the density of air at the top of Mount Everest. (Air on top of Everest does not form a black hole, because there is not enough of it; one would require an accumulated 6.5 billion solar masses.) Some drastic and superluminal new physical process would need to take over in such a low-density regime to instantly convert the collapsing cloud into a massive remnant instead of allowing a black hole to form.

A related idea is that something could cause black holes to change into massive remnants containing the original information after they form but long before they evaporate. But once again, this story requires nonlocal transfer of information from the interior of the initial black hole to the final remnant.

Despite the problems with these scenarios, physicists have explored versions of both of them. For example, in 2003 Samir Mathur put forward a proposal based on string theory, which posits that fundamental particles are tiny strings. His idea is that a black hole transforms into a "fuzzball," a kind of massive remnant, or that a fuzzball forms instead of a black hole in the first place. Thanks to the complicated physics of string theory and its allowance for more than the traditional four dimensions of spacetime, fuzzballs might have a complex higher-dimensional geometry; instead of the sharp traditional boundary of a black hole at the event horizon, a fuzzball would have a fuzzier and larger boundary where one encounters strings and higher-dimensional geometry.

Alternatively a more recent version of a remnant scenario is the proposal that instead of a black hole with an event horizon, a massive remnant forms with a surface "firewall" of high-energy particles where the horizon would be. This firewall would incinerate anything that encountered it, turning it into pure energy

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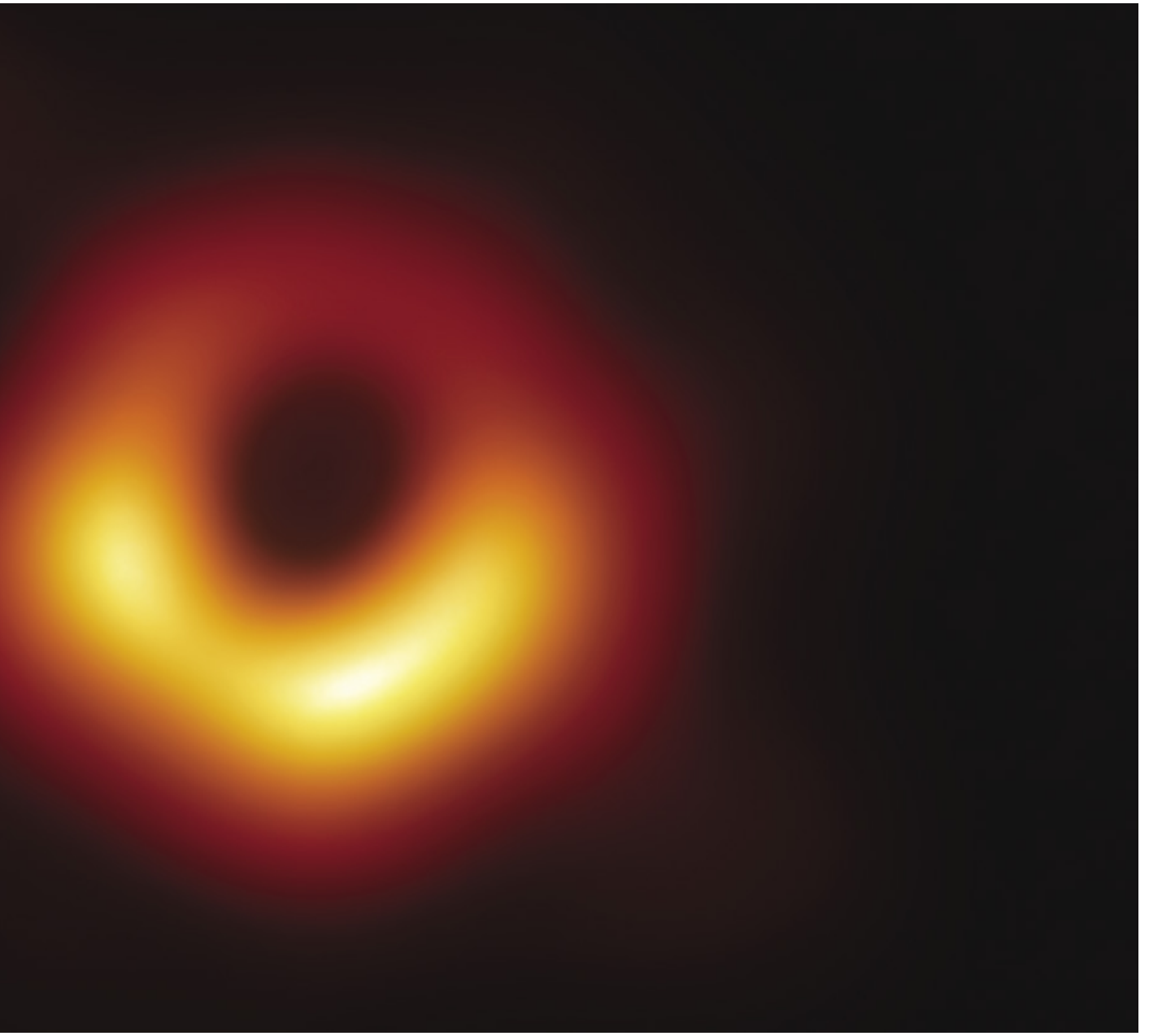

GRAVITY BENDS light around an apparent black hole at the center of the M87 galaxy in this seminal image from the Event Horizon Telescope.

that added to the firewall. Both the firewall and the fuzzball, though, share the problem of needing locality violation, and the resulting objects would have other properties that are very hard to explain.

MODIFYING LOCALITY

A COMMON THREAD in massive-remnant proposals is that saving quantum mechanics appears to require violation of the locality principle. But doing so carelessly is expected to be as disastrous as modifying quantum mechanics and, in fact, typically leads to another paradox. Specifically, the laws of relativity say that if you send a faster-than-light signal in empty, flat space, observers traveling past you at a high-enough speed will see the signal going backward in time. The paradox arises because this superluminal signaling then allows you to send a message into your past, for example, asking someone to kill your grandmother before your mother is born.

Even though this kind of answer appears to contradict fundamental physical principles, it is worth a closer look. Modifying locality seems crazy, but we have not found an alternative that does not. The severe nature of the black hole crisis strongly suggests a resolution via some subtle violation of the locality principle, one that does not produce such paradoxes. Put differently, quantum mechanics implies information is never destroyed, so information that falls into a black hole *must* ultimately escape, possibly through some new, subtle "delocalization" of

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information that might become clear when we can finally find a way to unify quantum mechanics and gravity—one of the most profound problems of present-day physics. In fact, we have other reasons to think such a subtlety could be at work. The very idea of localized information—that it can exist in one place and not in another—is more delicate in theories that include gravity than in those that do not, because gravitational fields extend to infinity, complicating the concept of localization.

If information does escape black holes, it might not require a change as obvious and abrupt as the formation of a massive remnant, whether fuzzball, firewall or another variant. The growing evidence for black holes suggests there are objects in the universe that look and act a lot like classical black holes, without large departures from Albert Einstein's predictions. Is Einstein's general relativity so drastically wrong in its description of black holes, or might there be some more innocuous, currently unknown effects that delocalize information and allow it to leak from black holes, avoiding such a dramatic failure of the entire spacetime picture?

OUR VERY NOTIONS OF SPACE AND TIME, WHICH UNDERLIE THE REST OF SCIENCE, APPEAR TO REQUIRE SIGNIFICANT REVISION.

In my recent theoretical work, I have found two versions of such effects. In one, the geometry of spacetime near a black hole is altered, making it bend and ripple in a way that depends on the information in the black hole—but gently, so that it does not, for example, destroy an astronaut falling through the region where the horizon would ordinarily be found. In this "strong, nonviolent" scenario, such shimmering of spacetime can transfer the information out. Interestingly, I have also found that there is a subtler, intrinsically quantum way for information to escape the black hole. In this "weak, nonviolent" scenario, even tiny quantum fluctuations of the spacetime geometry near the black hole can transfer information to particles emanating from the hole. The fact that the information transfer is still large enough to save quantum mechanics is related to the huge amount of possible information a black hole can contain. In either picture, a black hole effectively has a "quantum halo" surrounding it, where interactions pass information back to its surroundings.

Notably, these scenarios, despite appearing to require superluminal travel of information, do not necessarily produce a grandmother paradox. The information signaling here is tied to the existence of the black hole, which has a spacetime geometry that is different from that of flat space, so that the earlier argument about communicating with the past no longer holds. These possibilities are tantalizing from another perspective: the locality principle is also what prohibits our own faster-than-light travel; the quantum mechanics of black holes seems to be telling us there is something wrong with the present formulation of this principle.

REWRITING THE LAWS OF PHYSICS

SO FAR SUCH A QUANTUM HALO scenario has not been predicted by a more complete theory of physics that reconciles quantum mechanics with gravity, but it is strongly indicated by the need to resolve the problem and by assumptions based on what we see. If such a scenario is correct, it probably represents an approximate description of a deeper reality. Our very notions of space and time, which underlie the rest of science, appear to require significant revision. The current work to understand black holes may be akin to the first attempts to model the physics of the atom by Bohr and others. Those early atomic descriptions were also approximate and only later led to the profound theoretical structure of quantum mechanics. Although modifying locality seems crazy, we might find solace by noting that the laws of quantum mechanics also seemed very crazy to the classical physicists grappling with their discovery.

Given the immense challenge in sorting out the story of quantum black holes and the more complete theory describing them, physicists are eager for experimental and observational evidence to help guide us. The exciting recent advances have given humankind two direct observational windows on black hole behavior. In addition to the EHT's images of black holes, the Laser Interferometer Gravitational-wave Observatory (LIGO) and its companion facilities have begun to detect gravitational waves from collisions between apparent black holes. These waves carry valuable information with them about the properties and behavior of the objects that created them.

From a naive viewpoint, it seems preposterous that the EHT or LIGO could detect any departure from Einstein's description of black holes. Traditionally his theory has been expected to need modification only when spacetime curvatures become extremely large, near the center of a black hole; in contrast, curvatures are very weak near the horizon of a large black hole. But the information crisis I have described suggests otherwise. A large part of the theoretical community has now reached the consensus that some changes to the current laws of physics are needed to describe phenomena not just deep inside a black hole but all the way out past the horizon. We appear to have crossed the Rubicon. For the case of the black hole in M87, the distance at which we expect to find deviations from classical predictions is several times the size of our solar system.

Already LIGO and the EHT have ruled out wilder possibilities that could be considered in an attempt

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to give a logically consistent description of black holes. Specifically, if black holes were replaced by massive remnants more than about twice the diameter of the supposed black hole, we would have seen signs in the data from both experiments. In the case of the EHT, much of the light that produced the now famous image comes from a region around one and a half times the diameter of the event horizon. And for LIGO, part of the gravitational-wave signal that we detect is likewise produced from the region where the colliding objects reach similarly small separations. Although study of these signals is still in early phases, the EHT and LIGO have revealed very dark and very compact objects that produce signals just like those predicted for unmodified black holes.

Still, it is important to investigate these signals more closely. Sufficiently careful analysis might in fact uncover more clues about the quantum physics of black holes. Even if no new effects are observed, we then have information that constrains possible descriptions of their quantum behavior.

Sufficiently large-diameter remnants are now ruled out, but what about remnant scenarios that modify the black hole description only very near the horizon? Although a complete discussion would require a fuller theory of these remnants—such as fuzzballs or firewalls—we have some initial indicators. Specifically, if these objects had radii barely larger than the radius of the corresponding black hole horizon, then it is likely that neither EHT nor LIGO observations would be able to reveal such a structure because very little light or gravitational radiation escapes from the region very near the horizon.

One possible exception is the possibility of gravitational "echoes." As first suggested in 2016 by Vitor Cardoso of the University of Lisbon, Edgardo Franzin of the International School for Advanced Studies in Trieste, Italy, and Paolo Pani of the Sapienza University of Rome, if two such remnants combine to form a final remnant that has similar properties, gravitational waves can reflect off the merged remnant's surface and might be observed. Although most near-horizon scenarios are hard to rule out through observation, it is difficult to explain how such structures could be stable, instead of collapsing under their own weight to form black holes. Of course, this is a general problem for all massive-remnant scenarios, but it becomes even more challenging in the presence of the extreme forces in such a collision.

Prospects are better for testing some of the scenarios where new interactions behave like subtle modifications of spacetime geometry but extend well outside the horizon. For example, in the strong, nonviolent scenario, the rippling of a black hole's quantum halo can distort light passing near the black hole. If this scenario is correct, the shimmering could cause distortions of the EHT's images that change with time.

In my work with Dimitrios Psaltis of the University of Arizona, we found that these changes could happen over roughly an hour for the black hole in the center of our galaxy. Because the EHT combines multihour observations into an average, such effects may be hard to see. But the relevant fluctuation time for the black hole in M87, which is more than 1,000 times larger, is more like tens of days. This work suggests we should look for these distortions by using longer-duration EHT observations than the project's initial seven-day span. If the experiment found such distortions, they would be a spectacular clue to the quantum physics of black holes. If they do not appear, that will begin to point to the subtler weak quantum scenario or to something even more exotic.

The weak, nonviolent scenario is harder to test because of the relative smallness of the expected changes to the geometry. Yet preliminary investigation shows that this scenario can alter how gravitational waves are absorbed or reflected, possibly yielding an observable modification to gravitational-wave signals.

If either scenario is correct, we will learn more not only about what quantum black holes are but also about the deeper laws of nature. Right now we do not fully understand how to think about information localization when gravitational fields are present. Quantum physics suggests that spacetime itself is not a fundamental part of physics but instead arises only as an approximation of a more basic mathematical structure. Evidence for quantum black hole effects could help make this concept more concrete.

To learn more, it is important to extend and improve both EHT and gravitational-wave measurements. For the EHT, it would be useful to have significantly longer-duration observations, as well as images of other targets such as our galaxy's central black hole, both of which are anticipated. For gravitational waves, more observations with increased sensitivity would be helpful and will be assisted by a new detector in Japan and one due to launch in India, adding to the existing facilities in the U.S. and Europe. Furthermore, a strong complementary theoretical effort is needed to refine scenarios, to better clarify their origins and explanations, and to assess more thoroughly the question of how significantly they can affect EHT or gravitational-wave signals.

Whatever the resolution to the crisis, black holes contain crucial clues to the basic quantum physics of gravity, as well as to the very nature of space and time. Just as with the atom and quantum mechanics, a better understanding of black holes is likely to help guide the next conceptual revolution in physics. EHT and gravitational-wave observations have the potential to provide us with key information, either by ruling out quantum black hole scenarios or by discovering new phenomena associated with them. SA

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Finally, the Face of a Black Hole

After more than a decade of effort, a global network of radio telescopes revealed the first-ever picture of an enigmatic hole in spacetime

By Seth Fletcher

IT ACTUALLY WORKED.

The Event Horizon Telescope (EHT) has always sounded like an unlikely proposition: create a virtual Earth-size telescope to take a picture of the shadow of a black hole. Every piece of that sentence is a little bit absurd.

But it worked. After more than a decade of technical development and fundraising and astronomer herding and telescope wrangling, the astronomers of the EHT unveiled the first picture of a black hole—a bubble of pure gravity, a hole in spacetime, a prediction of general relativity so strange that Albert Einstein himself long refused to believe the concept was possible.

In six simultaneous press conferences on four continents, astronomers lit up projection screens with an image that, for experts at least, is unmistakable: a dark circle surrounded by a ring of light and lopsided fiery blobs, clumps of matter heated to 100 million degrees and circling the black hole at close to the speed of light.

Technically, this is a picture of the *shadow* of a black hole: specifically, a supermassive black hole—a 6.5-billion-solar-mass beast—55 million light-years from Earth at the center of the galaxy Messier 87. Black holes trap everything that falls in, including light, which is why they are black. In a sense, they are fundamentally unseeable, one-way cosmic escape hatches leading to ... well, that part is unclear. But because of the way they warp spacetime, they impose a dark silhouette on the glowing, superheated matter that circles them. This is the barely imaginable scene the EHT captured during an observing run almost four years ago and revealed to the world two years later.

Since the 1960s, when indirect astronomical evidence and breakthroughs in theoretical physics made the existence of black holes all but undeniable, these objects have been in a kind of epistemological limbo: they were the most likely explanation for all sorts of otherwise inexplicable phenomena, but no one held out much hope of ever seeing one.

That changed in the late 1990s, when astronomers around the world began building powerful high-frequency radio observatories on high ground in Hawaii, Mexico, Chile and the South Pole. Theoretical astrophysicists calculated that, in theory, uniting these telescopes using a technique called very-long-baseline interferometry would allow them to see the shadows of supermassive black holes that were sufficiently huge and close to Earth. The biggest prize has always been Sagittarius A*, the four-million-solar-mass black hole at the Milky Way's center. Sagittarius A* remains unseen—at least by the public. But M87, the only other known black hole within the EHT's grasp, has been captured.

Usually big scientific discoveries like this leak early, but this time the astronomers kept surprisingly tight control. France Córdova, director of the National Science Foundation—which has invested more than $28 million in the EHT over the years—saw the image for the first time at the press conference on the morning of April 10, 2019. It moved her to tears.

The NSF and other funding institutions promised that the EHT's result would be "groundbreaking," and it certainly was—the first direct evidence for the existence of event horizons, the defining feature of a black hole. But anyone hoping that this image would chip away at Einstein's ironclad theory of general relativity came away disappointed: the black hole looks pretty much exactly like the century-old theory says it should.

But this photograph is only a start. Since the 2017 observation, the EHT array has already grown in size and acuity, with a new telescope joining and another on the way and with the installation of ever more powerful digital-signal-processing hardware at each site. As Sera Markoff, an astrophysicist at the University of Amsterdam, said at the press conference, in the future all kinds of new telescopes will join the EHT to observe M87, Sagittarius A* and other black holes simultaneously in many different bands of light—radio, x-ray, gamma ray, infrared and optical.

It's also worth noting that in the two hours after the press conference, at least six scientific papers on the observation appeared online. They almost certainly contain clues and new questions that will take more time to process than a 24/7 news cycle can tolerate. For now, though, it's worth pausing for a moment to consider the strangeness of nature and the remarkable fact that these sentient, tool-using bipeds on a small world in a backwater solar system somehow managed to turn their planet into a telescope and take a picture of an exit chute from the universe. SA

Seth Fletcher is chief features editor at *Scientific American*. His book *Einstein's Shadow* (Ecco, 2018) is about the Event Horizon Telescope and the quest to take the first picture of a black hole.

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FIRST-EVER IMAGE of the shadow of the supermassive black hole at the heart of the galaxy Messier 87.

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MILKY WAY'S MONSTER, UNVEILED

Astronomers have revealed never before seen features of our galaxy's mysterious supermassive black hole

By Lee Billings

ESO, GRAVITY CONSORTIUM AND L. CALÇADA

GRAVITY INSTRUMENT on the European Southern Observatory's Very Large Telescope has discovered new details about the Milky Way's central supermassive black hole. This illustration visualizes some of them, chiefly newfound hot clumps of gas that orbit the black hole at 30 percent the speed of light.

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ASTRONOMERS HAVE DELIVERED THE BEST-YET VIEW OF A REAL-LIFE cosmic monster: Sagittarius A*, a supermassive black hole lurking at the center of the Milky Way—or rather a view of hot clumps of gas that orbit it, teetering on the edge of oblivion. The results reveal new, previously unknown properties of our galaxy's largest black hole and point the way toward a deeper understanding of gravity.

Black holes, like all truly terrifying monsters, can scarcely be comprehended, let alone seen. Even Einstein doubted they existed, despite his theory of general relativity predicting that they must. They are knots of gravitation bound so tightly that within them spacetime dissolves—spectral shadows so voracious they devour light itself. Yet they can be glimpsed indirectly, like apparitions at the corner of your eye. Most spectacularly, when they eat stars or other black holes, they can give off gravitational waves, ripples in the fabric of reality that scientists first directly detected in 2015. Scientists can also measure a black hole's mass through swarms of stars orbiting around it—showing, for example, that Sagittarius A* has somehow swallowed the equivalent of four million suns. (Those in other galaxies can be far larger, tipping the scales at billions of solar masses.) And, ironically, although black holes do not shine, the gas and dust that pile up in spinning accretion disks around their maws can be heated to billions of degrees, becoming hundreds of times more luminous than a star and occasionally ejecting even brighter sprays of radiation. When they come from supermassive black holes, those outbursts can shape and perhaps even sterilize a galactic host—and such black holes seem to squat at the center of every large galaxy. For more than 40 years astronomers have warily studied such circumstantial evidence like bones and ashes scattered at the threshold of a dragon's lair.

In 2018 an international team of scientists studied the Milky Way's monster using an instrument called GRAVITY to combine the infrared light from four eight-meter telescopes at the European Southern Observatory's Very Large Telescope in Chile. Combining light from multiple telescopes is a technique called interferometry and can dramatically boost the sensitivity and precision of astronomical observations. The results appeared in October 2018 in *Astronomy & Astrophysics*. "This is a major breakthrough," says Reinhard Genzel, an astrophysicist at the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, and leader of the group. "We have observed the galactic center by using four telescopes as a gigantic single telescope with an effective 130-meter diameter to make interferometric images about 1,000 times fainter than what has been done before." This is not the first breakthrough from GRAVITY: in May 2018 the team successfully measured the relativistic distortion of light from a star, S2, during its closest approach to Sagittarius A* in its 16-year orbit around the monstrous black hole.

The discovery unfolded during and shortly after those same observations of S2, when GRAVITY team members Oliver Pfuhl and Jason Dexter, study co-authors then both at Max Planck, noticed three flares, or "hotspots," that emanated from Sagittarius A*'s accretion disk between mid-May and late July 2018. To appreciate the GRAVITY team's feat, imagine looking up at the moon from Earth and discerning on the lunar surface a quarter coin (Sagittarius A*—or at least its shadow) sitting on a beach ball decorated with Christmas lights (Sagittarius A*'s accretion disk and accompanying flares).

These hotspots are thought to be "magnetic thunderstorms" that occur when intense magnetic fields form filaments that snap apart and reconnect, releasing copious energy to heat nearby gas within a black hole's accretion disk. Each hotspot is akin to a short-lived, 10-million-kilometer-wide lightbulb—after perhaps an hour, it cools and is sheared apart in the whirling, turbulent maelstrom. That would make studying them exceedingly challenging—particularly if their emissions

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were being warped and occluded by various extreme relativistic effects predicted to arise in the vicinity of a black hole. Those same effects, in turn, could be studied to put Einstein's theory of gravity to increasingly stringent tests, potentially leading to new physics.

Such outbursts have been detected before, but for the first time GRAVITY allowed the astronomers to precisely measure the flares' positions and motions before they dissipated, showing that each one moved at 30 percent light-speed in a roughly 45-minute orbit around some unseen central object weighing four million suns. GRAVITY's data also measured each flare's polarization, which shifted in accordance with each spot's motion through the disk's powerful magnetic fields, further reinforcing the orbital interpretation. "When we saw the first one, we had to ask ourselves, 'Is this real or not?' But then we found two more," Pfuhl says. "They all showed the same rotation, the same orientation and the same scale, which reassured us."

When first presented with the data, Genzel initially reacted with shock. "I couldn't believe my eyes," he says. "No one believed we could do this—we didn't really think we could do it, either—but there it was, this beautiful orbital motion." Besides being fortunate enough to catch multiple flares in the act, the GRAVITY team also seems to have been blessed with a quirk of geometry: their best estimates of the hotspots' orbits suggest Sagittarius A*'s accretion disk is coincidentally oriented almost face-on rather than edge-on to Earth, allowing astronomers to study its swirling hotspots much like meteorologists use satellite views to track thunderstorms in a hurricane. "This is like winning the lottery because the a priori probability that you would see something like this face-on is very low," Genzel says. "It almost seems that somebody has arranged this for us; I guess the galactic center is a place for lucky people."

One person relatively unsurprised by the result is Avi Loeb, an astrophysicist at Harvard University, who was not directly involved with GRAVITY's studies. More than a decade ago, while working with then postdoc Avery Broderick (now at the Perimeter Institute for Theoretical Physics in Ontario), Loeb developed models of hotspots around Sagittarius A* and suggested methods for observing their orbital motion. "Seeing is believing," he says. "This is fully consistent with what we expected.... Most everyone I talked to about this back then regarded our hotspot model as naive, but amazingly enough nature has proved kinder than many of my colleagues."

The most important overlap between such predictions and GRAVITY's observations is that Sagittarius A*'s hotspots seem to be perched just above a long-predicted point of no return—an "innermost stable orbit" for material at the accretion disk's inner cusp. Beyond this boundary any object will precipitously plunge down through the black hole's event horizon—the proverbial end of the line past which even light cannot escape—effectively passing out of the observable universe and into the unknown. Because the exact location of any black hole's innermost orbit depends on its most basic properties, GRAVITY's measurement is telling us something profound and new about Sagittarius A*. "By themselves, black holes are simple objects—mass, spin and [electric] charge is all you get," says Andrea Ghez, an astronomer at the University of California, Los Angeles, who leads a team that has used the twin Keck telescopes in Hawaii to compete with Genzel's group for more than a decade. "The innermost stable orbit is tied to the black hole's mass and spin—and we already know [Sagittarius A*'s] mass—so if you believe the hotspot is emitting from there, you could pin this black hole's spin and measure this fundamental property. That fundamental property is tied to how these things grow, which tells you how they form and evolve over time. Black holes are basic constituents of our universe, so when you study them, you are asking about the building blocks of the cosmos." (In 2020 Ghez and Genzel shared part of the Nobel Prize in Physics for their work monitoring Sagittarius A*.)

BLACK HOLES, LIKE ALL TRULY TERRIFYING MONSTERS, CAN SCARCELY BE COMPREHENDED, LET ALONE SEEN. EVEN EINSTEIN DOUBTED THEY EXISTED, DESPITE HIS THEORY OF GENERAL RELATIVITY PREDICTING THAT THEY MUST.

Unfortunately, for now further empirical validation of GRAVITY's result may be limited to that instrument alone. In 2012 NASA pulled the plug on an initiative to give the Keck telescopes an interferometric capability similar to that used by GRAVITY on the Very Large Telescope; without it, independent observations—and confirmation—from Ghez's team will likely have to wait until sometime in the 2020s when two as yet unbuilt 30-meter-class U.S. observatories, the Giant Magellan Telescope and the Thirty Meter Telescope, are slated to debut.

In the meantime, GRAVITY is continuing to observe the galactic center, and additional corroboration should eventually come from the realm of radio astronomy. The Event Horizon Telescope, an array of interlinked radio observatories around the world that made headlines in 2019 and 2020 with its unprecedented images of the supermassive black hole at the center of the M87 galaxy, has also sought to image Sagittarius A*. That work probes much closer to the black hole, where gravity traps light in a revolving ring just outside the event horizon. But according to the project's founding director, Sheperd Doeleman, those observations might also reveal radio blips produced by the circulation of hotspots farther out.

"Whether you're looking at them in infrared or radio or gravitational waves, black holes really are the crux, one of the universe's deepest and most profound mysteries," Doeleman says. "How can there be a one-way doorway out of our universe? What does that even mean? Right now we are still just seeing bones outside the dragon's lair—we haven't seen the dragon." SA

Lee Billings is a senior editor for space and physics at *Scientific American*.

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The Flare of Cosmic Collisions

In a controversial finding, astronomers claim they have glimpsed light from merging black holes

By Scott Hershberger

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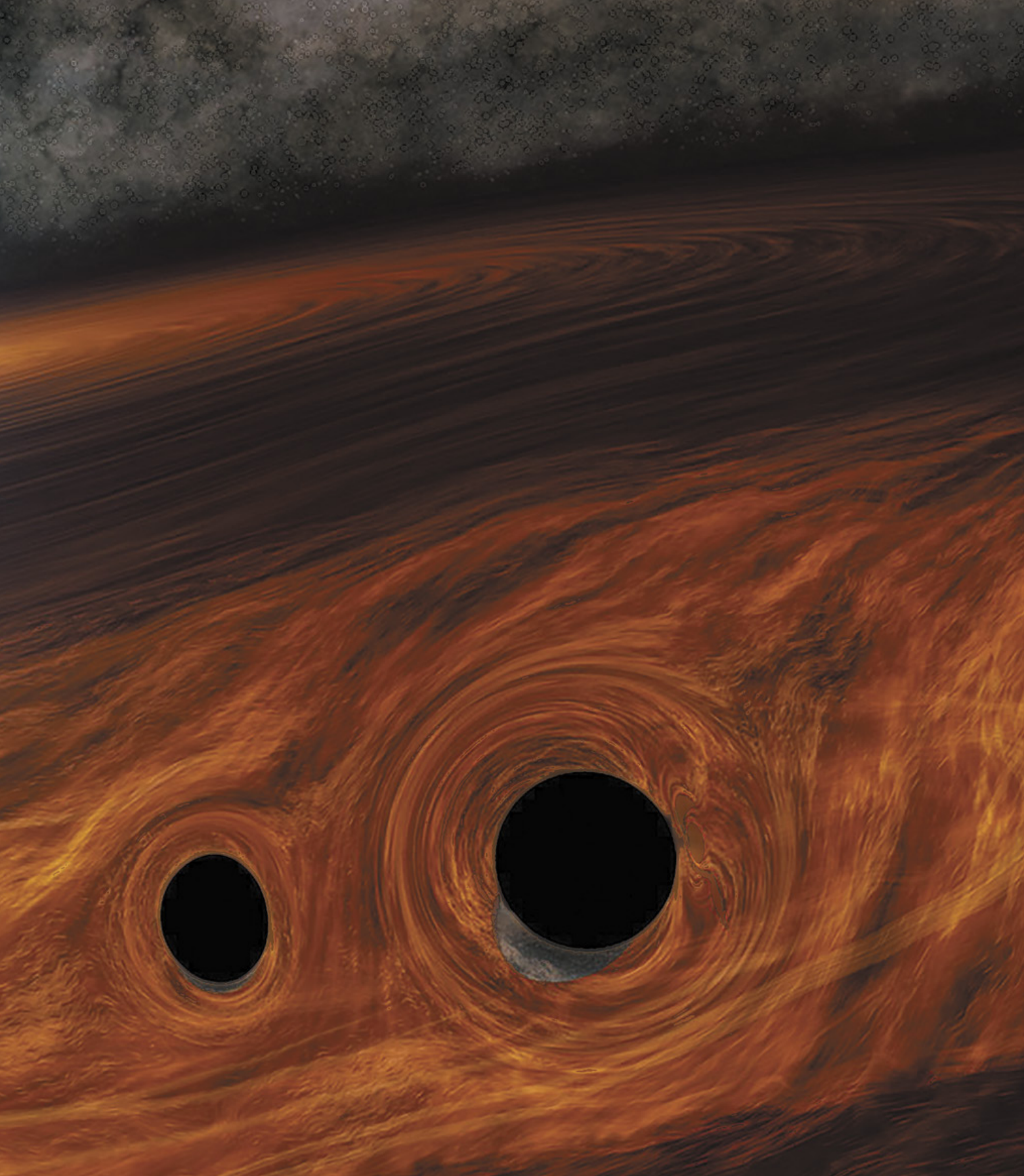

ARTIST'S IMPRESSION of two small black holes coalescing within a disk of gas and dust around a supermassive black hole.

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MORE THAN FOUR BILLION YEARS AGO A PAIR OF BLACK holes engaged in a dramatic dance. With gas and dust whirling around them, the voids spiraled closer and closer together, orbiting perilously near to a supermassive black hole. Then the two smaller black holes merged in a collision so powerful that it shook the fabric of space itself. As the resulting gravitational waves rippled toward Earth, the merged black hole recoiled like a rocket, heating the surrounding gas and generating a blinding flare of light that lasted for weeks.

That scenario was proposed in a paper published in June 2020 in *Physical Review Letters*. What researchers know for sure is that on May 21, 2019, they detected gravitational waves emitted by a collision of two black holes. And in the following weeks a strange flare of light emerged from the same region of the sky. If the flare did indeed come from the black holes, it marks the first time that scientists have seen light emitted in the aftermath of a black hole merger.

"I was stunned," says Jillian Bellovary, an assistant professor at Queensborough Community College, City University of New York, who was not involved in the work. "The idea is amazing. It's jaw-droppingly amazing." If confirmed, the finding offers a new direction for the fledgling field of multimessenger astronomy. By studying black holes and their surroundings with both gravitational waves and electromagnetic radiation, scientists expect to learn more than they could with either signal alone.

Scientists have long debated whether a binary black hole merger could trigger a flare of light in addition to gravitational waves. Most researchers agree that black holes colliding in a vacuum cannot produce light. But an active galactic nucleus, where the gravity of a supermassive black hole draws gas and dust into an immense accretion disk, would offer the perfect conditions to create a flare. "It's a whole new way of making black holes merge," says Chiara Mingarelli, who studies the celestial objects at the Center for Computational Astrophysics at the Flatiron Institute in New York City and was not involved with the research.

With this possibility in mind, researchers turned to the Zwicky Transient Facility (ZTF). Based at the Palomar Observatory in California, the facility photographs the entire northern sky every three nights and can spot any sudden changes in brightness. The team combed ZTF data in search of flares of light emanating from active galactic nuclei near black hole mergers that were previously detected by the Laser Interferometer Gravitational-wave Observatory (LIGO). In almost every case, the scientists found nothing. But in the aftermath of the May 2019 merger, an active galactic nucleus in the same region of the sky doubled in brightness. The researchers evaluated all the possible sources of the flare that they could think of and concluded that its most likely source was the merged black hole.

Still, they caution that they cannot be certain that their explanation is correct. And despite some scientists' enthusiasm, other experts are highly skeptical of the researchers' conclusion. "I just cannot understand how they would write the paper with that interpretation," says Avi Loeb, a theoretical physicist and the founding director of Harvard University's Black Hole Initiative. "It makes no sense."

A MERGER MYSTERY

LAST SUMMER'S ANNOUNCEMENT was not the first time astronomers thought they had seen light emitted by merging black holes. In 2015 the Fermi Gamma-ray Space Telescope spotted a faint burst of gamma rays coming from the same area as the very first black hole merger detected by LIGO. The signal sparked a flurry of speculation and competing explanations. Soon after, Loeb proposed that the pair of black holes had merged inside a star, which then provided the gas needed to emit the light. The research community remained unconvinced. Many scientists eventually conceded that

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the gamma-ray burst was likely a fluke—an emission from some separate background object that was completely unrelated to the black hole merger.

Loeb still thinks that under the right conditions, merging black holes could trigger a flare of light. But "I have a big problem with the suggestion that this flare was a result of accretion onto the [merged] black hole," he says. The brightness of astronomical objects typically has an upper limit, known as the Eddington luminosity. In some circumstances, this limit can be exceeded by a factor of up to several thousand. In the scenario proposed in the study, however, the merged black hole had a luminosity around 100,000 times the Eddington value. "That is unheard of," Loeb says.

Matthew Graham, project scientist at ZTF and lead author of the new paper, acknowledges that a luminosity so large would be unprecedented. But based on current knowledge, "it's not unrealistic. It's not beyond the bounds of possibility," he says. Although running reliable computer simulations of the complex interactions of binary black holes in an active galactic nucleus is not yet feasible, extrapolation from past simulations convinced Graham's team that its interpretation of the data was the most plausible.

"Reasonable people can disagree about it, but we can have a discussion," says Barry McKernan, a co-author of the paper and an astrophysicist at Borough of Manhattan Community College, C.U.N.Y. If the flare of light did not originate from merging black holes, it might have come from a "very, very unusual supernova," says study co-author K. E. Saavik Ford, also at Borough of Manhattan Community College. Another possible source is the natural variability of the active galactic nucleus, which is known to change in brightness over time. Loeb suspects the former scenario, whereas Zoltan Haiman of Columbia University favors the latter. Given the intensity and timing of the flare, both explanations seem highly unlikely to Ford and McKernan—though not impossible.

Unlike the gamma-ray burst in 2015, the new flare allowed the researchers to make predictions that will soon be put to the test. According to their model, at least one of the premerged black holes was spinning rapidly. "That's something that we have to have in order for our scenario to make any sense," McKernan says. The team also estimates the mass of the merged black hole to be around 100 times that of the sun. LIGO's full analysis of the gravitational-wave data will support or refute both assertions. Additionally, as the merged black hole orbits the supermassive one, it will eventually reenter the accretion disk, triggering another flare of light that would be visible from Earth. The team anticipates that this will happen sometime in the summer.

"The main thing I'm excited about is this concrete prediction," says Katerina Chatziioannou, a member of the LIGO team analyzing the gravitational waves from the event. "I'm waiting to see where that goes." If the second flare occurs as predicted, it will spark a new era in the study of active galactic nuclei.

UPDATES IN ULTRAVIOLET

BEYOND THE PROPERTIES of the black holes themselves, flares of light from merging black holes could reveal properties of the accretion disks in active galactic nuclei. From this first flare, Graham's team estimated the density of the gas and thickness of the disk—a calculation impossible to make with the gravitational-wave data alone. Future flares could offer other clues about the composition of active galactic nuclei, which "are really critical pieces of our understanding of how galaxies in our universe get built," Ford says.

But for multimessenger astronomy to flourish, astronomers must update their tools. Although ZTF detected a flare in the visible spectrum, Ford says that flares from other black hole mergers would be easier to spot in ultraviolet wavelengths. Because Earth's atmosphere absorbs most ultraviolet light before it can reach ground-based observatories, scientists must turn to space telescopes. Graham says NASA's Neil Gehrels Swift Observatory is the best candidate but an imperfect one: Swift was primarily designed to study gamma-ray bursts. And it has a much smaller field of view than the ZTF telescope.

IF THE FLARE DID INDEED COME FROM THE BLACK HOLES, IT MARKS THE FIRST TIME THAT SCIENTISTS HAVE SEEN LIGHT EMITTED IN THE AFTERMATH OF A BLACK HOLE MERGER.

A handful of other space telescopes that are sensitive to ultraviolet light dot the sky. None is ideal for searching for light flares in the wake of gravitational waves, however. "The ultraviolet has been kind of neglected by the [astronomical] community for a while," C.U.N.Y.'s Bellovary says. "That's a problem, honestly." She and others hope that the new research will spur the development of an ultraviolet telescope with a large field of view. "To have the appropriate satellite would cost a lot of money, but I would certainly advocate that we spend it," Ford says.

For now scientists await the LIGO results and predicted second flare. Erin Kara, an astrophysicist at the Massachusetts Institute of Technology, finds the black hole merger theory "tempting." Yet she is not ready to celebrate without more evidence. "Nature comes up with all sorts of crazy things that we can't explain," Kara says. "It's quite likely that we're just not creative enough to be able to think about all of the possibilities of things that could be causing these flares." SA

Scott Hershberger was a 2020 AAAS Mass Media Fellow at *Scientific American*.

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MYSTERY COSMIC HEAVYWEIGHT

Existing in the "mass gap" dividing two classes of stellar remnants, this strange object could be the most massive neutron star, the lightest-known black hole—or something else entirely

By Charlie Wood

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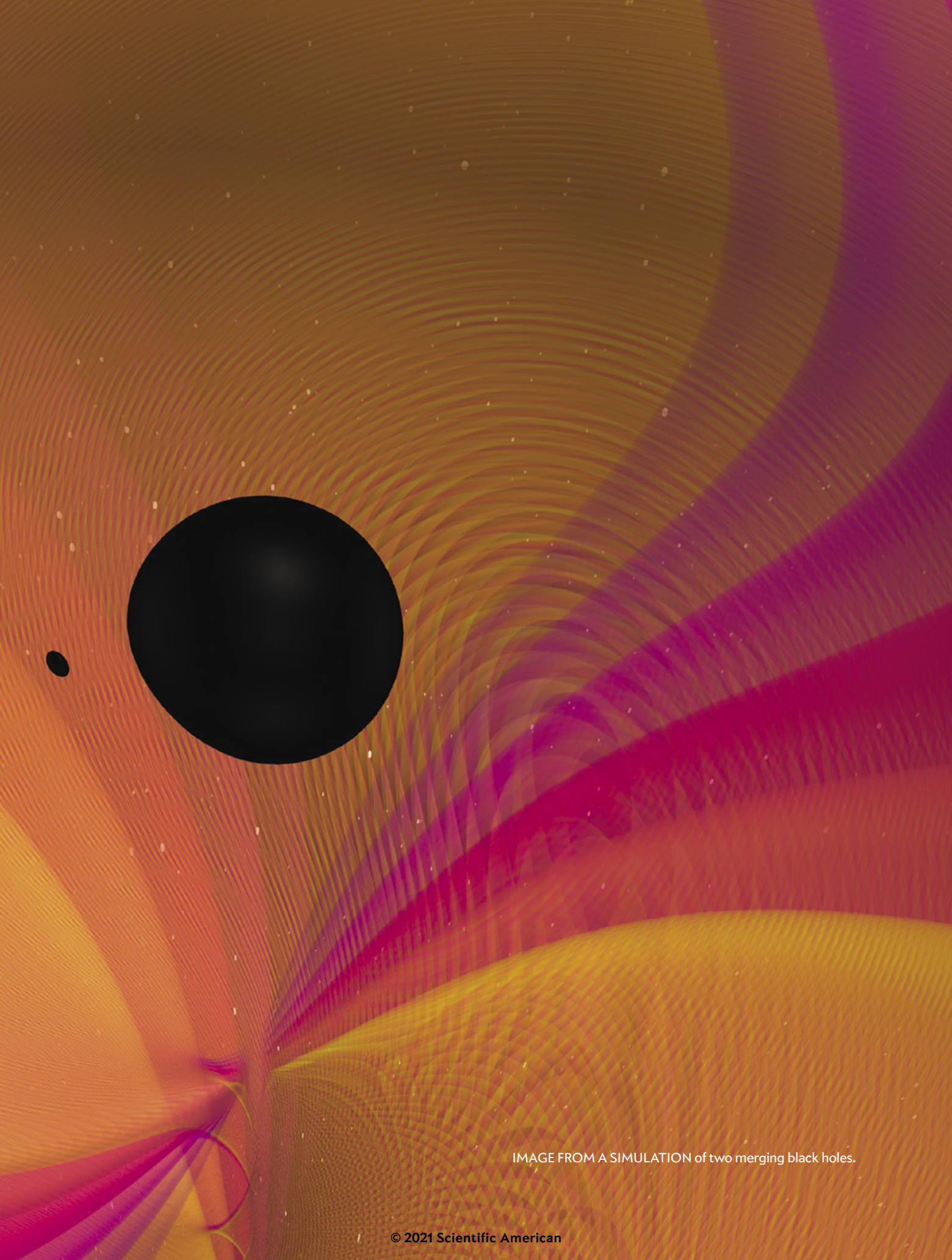

IMAGE FROM A SIMULATION of two merging black holes.

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FOR MORE THAN A DECADE ASTROPHYSICISTS HAVE WONDERED why nature appears to show an odd restraint in the way it slays stars. In life, they range from pip-squeaks to behemoths. Small ones simply burn out and fade away, but something more curious happens to the jumbo-size variety. When such a star dies, its great bulk causes its innards to implode as a core-collapse supernova. The process sparks a cataclysmic explosion and compresses some of the remains into astrophysical exotica—often a neutron star or, for the very heaviest suns, a black hole. Yet a pronounced rift appears to divide the weight classes of these two types of massive stellar corpses. Although astronomers have spotted neutron stars weighing up to around two solar masses and black holes as light as five, middleweight cadavers have gone entirely missing—until now.

In June 2020 the Laser Interferometer Gravitational-wave Observatory (LIGO) Scientific Collaboration announced the first conclusive detection of a stellar remnant falling into the so-called mass gap between neutron stars and black holes. After months of calculations, researchers at LIGO and the Virgo gravitational-wave detector in Italy concluded that such waves rippling through Earth in August 2019—an event dubbed GW190814 that was initially classified as a black hole consuming a neutron star—actually came from a 23-solar-mass black hole swallowing a mysterious 2.6-solar-mass object. Whether the smaller body is the heaviest known neutron star or the lightest known black hole—or a truly exotic beast, such as a star made of particles distinct from those of normal stars—its existence suggests that the theories describing the most extreme stellar fates need updating.

"I would rank this as definitely the most exciting announcement we've seen from LIGO since the original binary black hole discovery and then the first detection of a neutron star collision," says Duncan Brown, a gravitational-wave astronomer at Syracuse University, who was not involved in the research. "We're probing a new piece of astrophysical understanding of the universe."

The new finding hints that the cosmos may enjoy a wider freedom in how it disposes of stars than researchers had supposed. Whether that leeway means atomic building blocks have enough brawn to support more monstrous neutron stars or that supernovae can forge tinier black holes, LIGO's detection shrinks the gulf between those two most plausible scenarios.

"The idea of a mass gap as a true gap with nothing in it, I think, is getting progressively destroyed," says Philippe Landry, a LIGO member at California State University, Fullerton. "This is going to be one nail in the coffin."

From a fundamental physics perspective, the line separating neutron stars from black holes is razor-thin. If you toss an apple onto a neutron star at the

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Max Planck Institute for Gravitational Physics and Simulating Extreme Spacetimes (SXS) Collaboration

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limit of what its constituent neutrons can bear, it will abruptly collapse into a black hole. The heftiest known neutron star weighs 2.14 times the mass of our sun. And nuclear theorists suspect the objects can grow somewhat heavier, with the most optimistic models putting the complete breakdown of matter at 2.5 solar masses. Based on such theories, the LIGO collaboration calculated that the chance of the lighter partner in GW190814 being a neutron star is less than 3 percent. A neutron star that heavy, Landry says, would be a "complete game changer."

Although they would never be able to collect any winnings, most astrophysicists would bet that 2019's merger involved a big black hole gobbling up an improbably tiny one. But while nuclear theory makes that scenario more plausible than one involving a single black hole and a neutron star, it still challenges the best theories of how such systems come to be. "Basically," Landry says, "something's got to give."

As far as astrophysicists know, making a pint-size black hole—and then feeding it to a larger one—should pose a nearly insurmountable obstacle to the universe. A conceivable way of creating such a diminutive partner is to mash together two bulky neutron stars, an event LIGO witnessed in 2017. What are the chances, however, that a special matchmaking environment, such as a chaotic galactic center dense with stellar corpses, brought two neutron stars together—and also managed to set up the resulting mass-gap black hole with a much larger companion? "There's nothing that forbids it," says Feryal Özel, an astrophysicist at the University of Arizona, who is not involved with LIGO. "But it's more of a soap opera."

To many, the simplest option is that the mini black hole was born—as most black holes are—directly from the heart of a dying star. The basics of stellar death are simple: a star blows off a massive shell, leaving its core to crumple into a black hole or neutron star. But predicting the exact aftermath of a messy explosion involving gravity, thermodynamics and particle physics represents something of a cosmic final exam that astrophysicists are still working on. "Pick up the comprehensive encyclopedia of physics," Brown says, "and you will probably need almost every piece of physics in there to model a supernova."

So when a team led by Özel analyzed groups of known neutron stars and black holes in 2010 and concluded that none were likely to lie between two and five solar masses, supernova researchers jumped at the chance to place more meaningful limits on the inscrutable process. A rough picture emerged in which fast, violent explosions expelled most of a star's material cleanly, leaving the naked core to contract into a classic neutron star of perhaps two solar masses. In gentler cataclysms, however, some debris failed to escape and crashed back onto the neutron star. This material might (conveniently) add at least three solar masses, producing a black hole weighing—at minimum—as much as five suns.

Thus, the vacant zone became a tool for theorists, says Vicky Kalogera, an astrophysicist at Northwestern University and a LIGO member. She and her colleagues asked themselves, "What do I need to do to the core-collapse mechanism to create the gap?" she says.

LIGO's mass-gap discovery hints that perhaps they need not bother: a 2.6-solar-mass stellar black hole would suggest that no such rigid regulations apply. Supernovae may be free to search out the fundamental line between neutron stars and black holes after all, removing one onerous stipulation from the astrophysical final exam. "I think this thing pretty much says there isn't a mass gap," Brown says.

Nevertheless, the divide between neutron stars and black holes may well persist as a cosmic proclivity rather than a rule. If you looked naively at star sizes, Özel says, you would conclude that black holes should be everywhere. Their relative absence still suggests to her that supernovae likely conspire against them to some degree. "It could be that these objects are very difficult to make, but once in a blue moon, a supernova explosion lands you there," she says. Plus, researchers will still have to figure out why a mass gap seems to separate black hole and neutron star duos seen in x-rays but not those detected by gravitational waves.

Hard answers will come only with more detections of seemingly impossible objects. LIGO can tell tiny black holes from big neutron stars if the partners have a similar mass or give off a visible flash when they merge (colliding black holes are not expected to detonate with a burst of light, as merging neutron stars do, at least in principle). Even if ambiguous events continue to pile up, however, just watching where the masses fall will reveal a lot about what nature does with its leftover stars.

"After one weird system is discovered, then we need more of them," Kalogera says. SA

"I WOULD RANK THIS AS DEFINITELY THE MOST EXCITING ANNOUNCEMENT WE'VE SEEN FROM LIGO SINCE THE ORIGINAL BINARY BLACK HOLE DISCOVERY AND THEN THE FIRST DETECTION OF A NEUTRON STAR COLLISION."
—DUNCAN BROWN *SYRACUSE UNIVERSITY*

Charlie Wood is a journalist covering discoveries in the physical sciences both on and off the planet. His writing has appeared in *Quanta Magazine*, *Popular Science*, and elsewhere.

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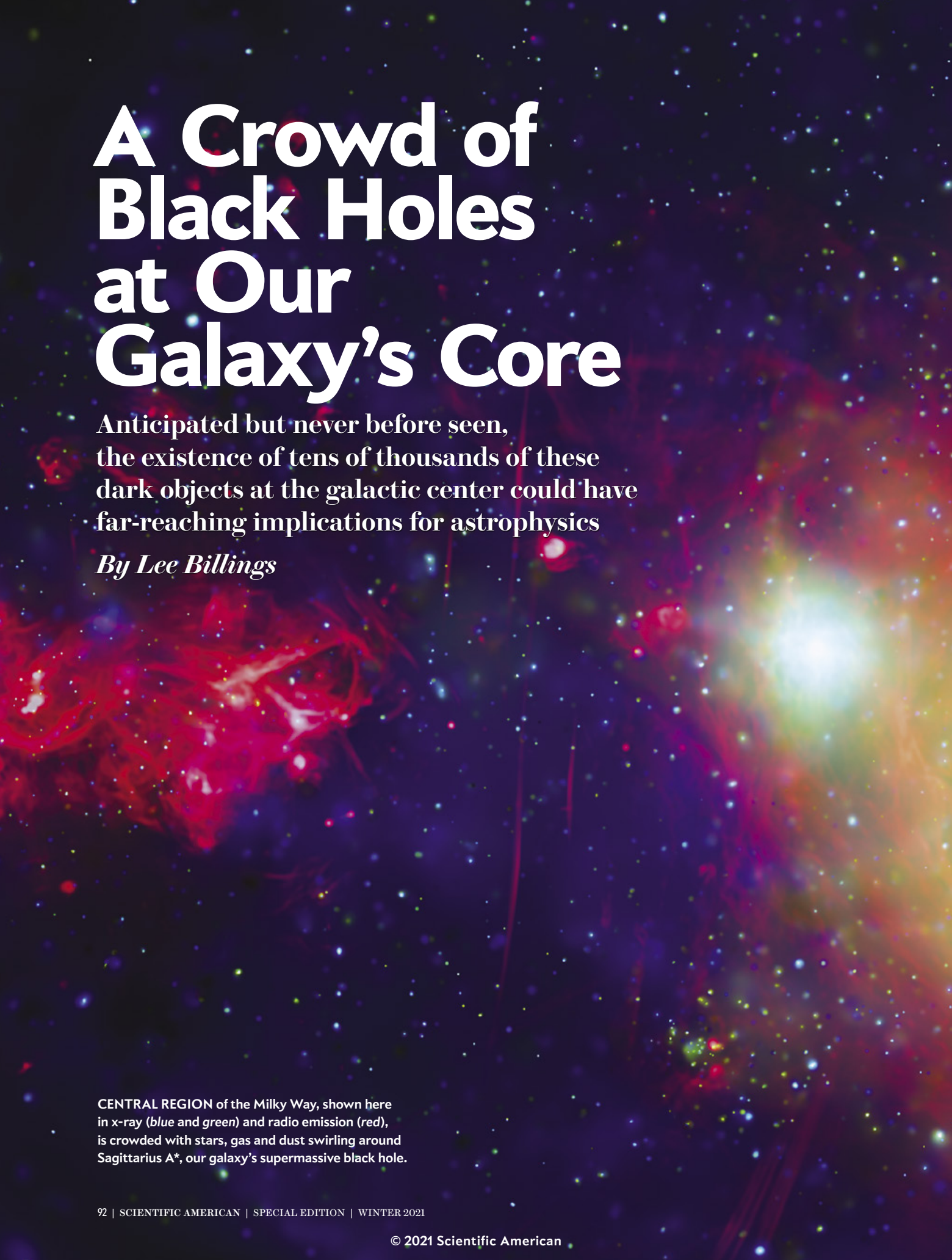
A Crowd of Black Holes at Our Galaxy's Core

Anticipated but never before seen, the existence of tens of thousands of these dark objects at the galactic center could have far-reaching implications for astrophysics

By Lee Billings



CENTRAL REGION of the Milky Way, shown here in x-ray (*blue* and *green*) and radio emission (*red*), is crowded with stars, gas and dust swirling around Sagittarius A*, our galaxy's supermassive black hole.

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FOR THE FIRST TIME ASTRONOMERS HAVE GLIMPSED A long-predicted population of black holes lurking at the heart of the Milky Way.

Scientists already knew that our galaxy's core holds a supermassive black hole weighing millions of times more than our sun and that this great beast is enveloped by a diverse entourage of lesser companions. Trapped in its gravitational clutches, run-of-the-mill stars whip around this gargantuan black hole like fireflies in a hurricane. So, too, do astrophysical exotica such as neutron stars and white dwarfs—the remnants left by normal stars when they die. Presumably black holes should be there as well, either born on the galactic center's doorstep from the deaths of massive stars or arriving via migration from farther out.

Such black holes should each weigh 10 to 20 times more than our sun. That bulk would make them behave a bit like heavy pebbles outpacing fine silt to the watery bottom of a well, jostling through the lighter surrounding stars to reach stable orbits very close to the Milky Way's core. Since the 1970s theorists studying this process have predicted a galactic center swarming with thousands of black holes bounded by an outer "cusp" beyond which the black holes' numbers should plummet. But despite their predicted prevalence, these black holes are so dark and quiescent that they have been all but undetectable against the galactic center's stellar splendor—at least, until now.

Using 12 years of archival data from NASA's Chandra X-Ray Observatory, a team led by Columbia University astrophysicist Charles J. Hailey has found a dozen potential black holes within a few light-years of the Milky Way's center, well within the gravitational reach of our galaxy's supermassive black hole. The team speculates these must be the first observational signs of the long-theorized cusp. Based on the emissions and spatial distribution of these 12 systems, the team estimates 10,000 to 20,000 of these objects should be swirling around our galaxy's core, mostly unseen. For perspective, apart from these newfound dozen scientists have identified only about 60 black holes in the entire Milky Way, and all but a few are far from the galactic center. The findings appeared in a paper in April 2018 in *Nature*.

PRECEDING PAGES: X-RAY: NASA, CXC, UMASS AND D. WANG ET AL.; RADIO: NRF, SARAO AND MEERKAT

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The study appears to vindicate predictions from theorists such as Mark Morris, an astrophysicist at the University of California, Los Angeles, who in 1993 penned a key paper predicting tens of thousands of stellar-mass black holes would form a disk around the galactic center. Across the decades, other theorists tackling the problem have arrived at similar estimates. "There hasn't ever been much controversy about this idea, because it's just an inevitable consequence of simple Newtonian dynamics," Morris says. "The only thing is, it has been really hard to prove."

"Finding evidence for a large number of black holes at the center of the Milky Way confirms a fundamental and major prediction of galactic dynamics," Hailey says. "These objects also provide a unique laboratory for learning about how big black holes interact with little ones because we can't readily study these processes in other, more distant galaxies."

Hailey and his team used Chandra data because black holes at the galactic center should be most visible via x-rays, produced when the black holes form a binary system with a low-mass star and feed on their captured companion.

Siphoned off by the black hole's gravitational pull, the star's outer layers will pile up outside the black hole's maw in a spiraling, steadily glowing disk. The intense x-ray emissions from these disks would be exceedingly faint when viewed from Earth's vicinity, sending only one photon apiece into Chandra's optics every five or 10 minutes. These weak emissions would also be intermixed with many other x-ray sources from the galactic center. To pin down the nature of their dozen candidates, Hailey's team plotted their spectral peaks and tracked their activity across time, finding patterns consistent with previous observations of binary black hole emissions elsewhere in the galaxy. The fact that there must then be tens of thousands of black holes at the galactic center stems from the notion that these objects would only very rarely be accompanied by a star to make them glow—most would remain isolated, invisible singletons.

Morris calls the work "exciting" but notes that because of the very low total numbers of photons used in the analysis, of the 12 putative black holes some might actually merely be statistical flukes produced by coincidentally timed emissions from other sources. Hailey, too, admits that of the dozen sources detected he feels certain only half are black holes—the remaining six, he says, display behavior that could also be explained as emissions from rapidly spinning neutron stars called millisecond pulsars.

Despite such uncertainty, Jordi Miralda-Escudé, an astrophysicist at the University of Barcelona unaffiliated with the work, says the results should have profound implications for future research. "A discovery like this will always have consequences that we cannot at present predict," he says. "If confirmed, the existence of these black holes suggests similar concentrations should exist in the centers of most galaxies throughout the universe." Such confirmations could come from perhaps another decade of additional Chandra observations or from studies by Chandra's proposed successor, a space telescope called Lynx that NASA is studying for potential development and launch in the 2020s or 2030s.

"THERE HASN'T EVER BEEN MUCH CONTROVERSY ABOUT THIS IDEA, BECAUSE IT'S JUST AN INEVITABLE CONSEQUENCE OF SIMPLE NEWTONIAN DYNAMICS. THE ONLY THING IS, IT HAS BEEN REALLY HARD TO PROVE."

—MARK MORRIS *UNIVERSITY OF CALIFORNIA, LOS ANGELES*

Scientists studying gravitational waves would likely benefit the most from further studies of black holes hidden at the Milky Way's core. Predicted by Albert Einstein more than a century ago, these elusive ripples in spacetime have only recently been observed, and the majority of detections to date have been traced to merging black holes billions of light-years away. Mysteriously, most of these black holes are inconveniently sized, appearing too large to have readily formed directly from dying massive stars. Alternative explanations posit that these anomalously massive black holes grew and merged in throngs of stars called globular clusters, but that process can easily require more time than the current age of the universe. "So how do you get these things?" Morris says. "Hundreds of papers have been written already speculating about this. But if you have clusters of black holes at the centers of galaxies, there are mechanisms by which some could rapidly grow, form binaries and merge with each other."

Regardless of how scientists follow up this discovery, one way or another the result will be "pinning down the number of black holes in the center of a normal galaxy like the Milky Way," Hailey says. "That will be invaluable, especially for researchers trying to calculate the nature and number of gravitational-wave events expected from galaxy cores. All the information astrophysicists need is right there, at the center of our galaxy." SA

Lee Billings is a senior editor for space and physics at *Scientific American.*

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HERE COME THE WAVES

After a clutch of historic detections, gravitational-wave researchers have set their sights on some ambitious scientific quarry

By Davide Castelvecchi

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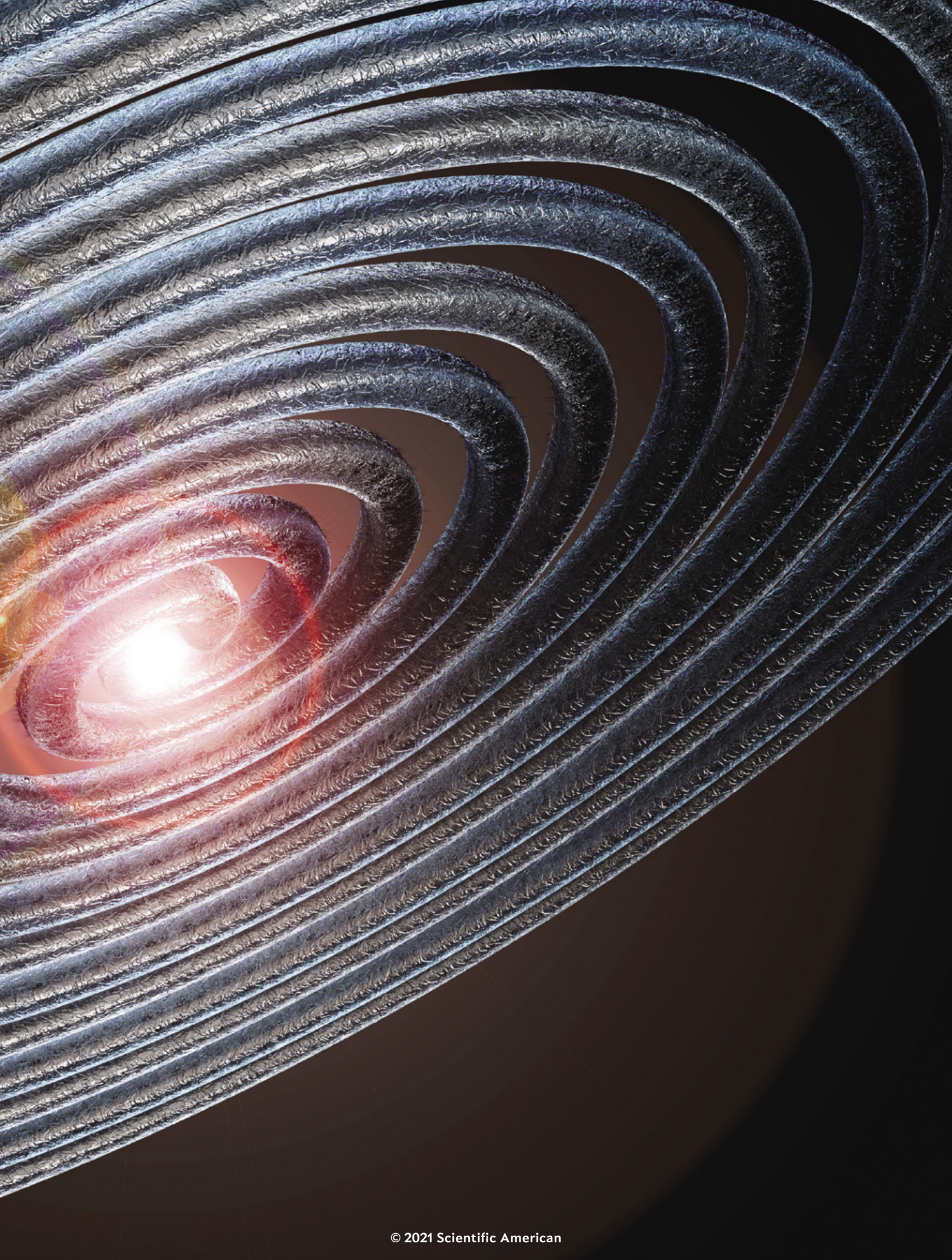

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IN THE MID-1980S BERNARD SCHUTZ CAME UP WITH A NEW SOLUTION TO ONE OF astronomy's oldest problems: how to measure the distance from Earth to other objects in the cosmos. For generations, researchers have relied on an object's brightness as a rough gauge of its distance. But this approach carries endless complications. Dim, nearby stars, for example, can masquerade as bright ones that are farther away. Schutz, a physicist at Cardiff University in Wales, realized that gravitational waves could provide the answer. If detectors could measure these ripples in spacetime emanating from interacting pairs of distant objects, scientists would have all the information needed to calculate how strong the signal was to start with—and thus how far the waves must have traveled to reach Earth. Therefore, he predicted, gravitational waves could be unambiguous markers of how quickly the universe is expanding.

His idea was elegant but impractical: nobody at the time could detect gravitational waves. But in August 2017 Schutz finally got the opportunity to test this concept when the reverberations of a 130-million-year-old merger between two neutron stars passed through gravitational-wave detectors on Earth. As luck would have it, the event occurred in a relatively nearby galaxy, producing a much cleaner first measure than Schutz had dreamed. With that one data point, Schutz was able to show that his technique could become one of the most reliable for measuring distance. "It was hard to believe," he says. "But there it was."

More mergers like that one could help researchers resolve an ongoing debate over how fast the universe currently is expanding. But cosmology is just one discipline that could make big gains through detections of gravitational waves in the coming years. With a healthy bunch of discoveries already under their belts, gravitational-wave scientists have a long list of what they expect more data to bring, including insight into the origins of the universe's black holes, clues about the extreme conditions inside neutron stars, a chronicle of how the universe structured itself into galaxies, and the most stringent tests yet of Einstein's general theory of relativity. Gravitational waves might even provide a window into what happened in the first few moments after the big bang.

Researchers have started working down this list with the help of the U.S.-based Laser Interferometer Gravitational-wave Observatory (LIGO), the Virgo observatory near Pisa, Italy, and a similar detector in Japan that began making observations in late 2020. They will get an extra boost from space-based interferometers and from terrestrial ones that are still on the drawing board—as well as from other methods that could soon start producing their own first detections of gravitational waves.

Like many scientists, Schutz hopes that the best discoveries will be ones that no theorist has even dreamed of. "Any time you start observing some-

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thing so radically new, there's always the possibility of seeing things you didn't expect."

SPINNING CLUES

FOR A FIELD of research that is just over five years old, gravitational-wave astronomy has delivered discoveries at a staggering rate, outpacing even the rosiest expectations. In addition to the discovery in 2017 of the neutron star merger, LIGO and Virgo have recorded four dozen pairs of black holes coalescing into larger ones since 2015 [*see box on page 100*]. The discoveries are the most direct proof yet that black holes truly exist and have the properties predicted by general relativity. They have also revealed, for the first time, pairs of black holes orbiting each other.

Researchers now hope to find out how such pairings came to be. The individual black holes in each pair should form when massive stars run out of fuel in their cores and collapse, unleashing a supernova explosion and leaving behind a black hole with a mass ranging from a few to a few dozen suns.

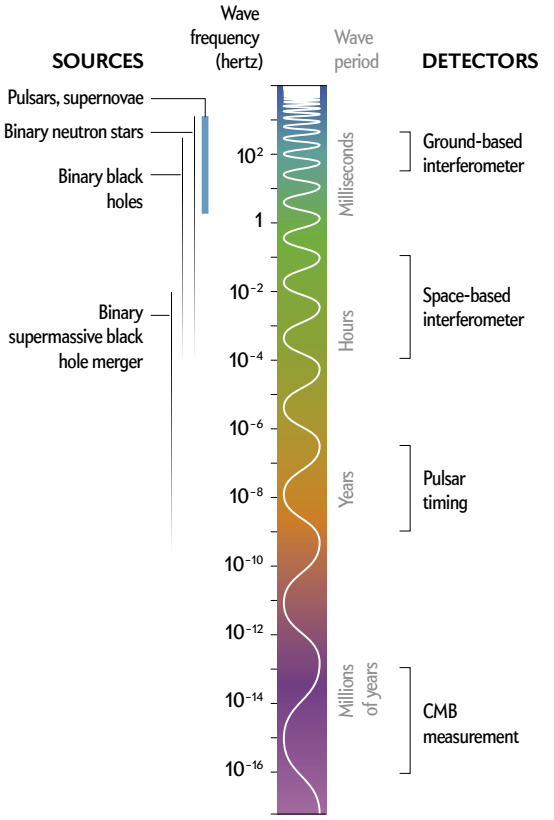
There are two leading scenarios for how such black holes could come to circle each other. They might start as massive stars in each other's orbit and stay together even after each goes supernova. Alternatively, the black holes might form independently but be driven together later by frequent gravitational interactions with other objects—something that could happen in the centers of dense star clusters.

Either way, the objects' energy gradually disperses in the form of gravitational waves, a process that pulls the pair into an ever tighter and faster spiral, eventually fusing into a single, more massive black hole. Ilya Mandel, a theoretical astrophysicist at Monash University in Melbourne, Australia, says that for LIGO and Virgo to see such pairs merge, typical black holes need to have started their mutual orbit separated by a distance of less than one quarter that between Earth and the sun. "If you start out with the two black holes any farther apart, it will take longer than the age of the universe" for them to merge, Mandel says.

The black hole mergers discovered so far are not sufficient to determine which formation scenario dominates. But in an analysis of the first three detections, a group including Mandel and Will M. Farr, a theoretical astrophysicist and LIGO member at Stony Brook University, suggested that just five more observations could provide substantial evidence in favor of one scenario or the other. This would involve scrutinizing the gravitational waves for clues about how black holes rotate: those that pair up after forming independently should have randomly oriented spins, whereas those with a common origin should have spin axes that are parallel to each other and roughly perpendicular to the plane in which they orbit.

The Gravitational-Wave Spectrum

Much like electromagnetic waves, gravitational waves are emitted by many different objects over a wide range of frequencies. Terrestrial interferometers such as the Laser Interferometer Gravitational-wave Observatory (LIGO) and Virgo are sensitive to only a subset of those frequencies, which limits their ability to "see" certain cosmic phenomena. They will not detect collisions of supermassive black holes found in the hearts of galaxies, for example. But space-based interferometers and other approaches for picking up gravitational waves could extend physicists' reach.



Further observations provided insight into some of the fundamental questions about black hole formation and stellar evolution. Collecting many measurements of masses should reveal gaps—ranges in which few or no black holes exist, says Vicky Kalogera, a LIGO astrophysicist at Northwestern University. In particular, "there should be a paucity of black holes at the low-mass end," she says, because relatively small supernovae tend to leave behind neutron stars, not black holes, as remnants. And at the high end—around 50 times the mass of the sun—researchers expect to see another cutoff. In very large stars, pressures at the core are thought to eventually produce antimatter, causing an explosion so violent that the star simply disintegrates without leaving any remnants at all. These events, called

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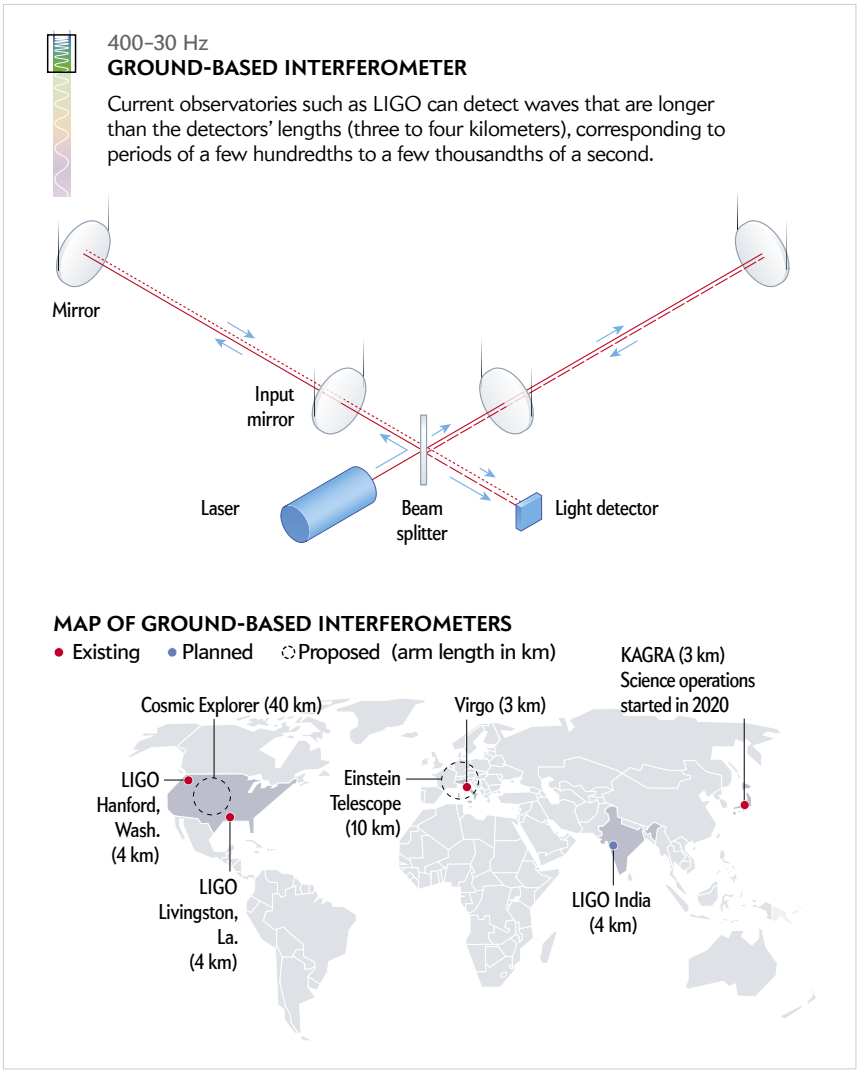
400–30 Hz
GROUND-BASED INTERFEROMETER
Current observatories such as LIGO can detect waves that are longer than the detectors' lengths (three to four kilometers), corresponding to periods of a few hundredths to a few thousandths of a second.
Mirror
Input mirror
Laser
Beam splitter
Light detector
MAP OF GROUND-BASED INTERFEROMETERS
Existing
Planned
Proposed (arm length in km)
Cosmic Explorer (40 km)
Virgo (3 km)
KAGRA (3 km) Science operations started in 2020
LIGO Hanford, Wash. (4 km)
Einstein Telescope (10 km)
LIGO Livingston, La. (4 km)
LIGO India (4 km)

pair-instability supernovae, have been theorized, but so far there has been scant observational evidence to back them up.

Since then, however, the LIGO and Virgo teams have detected systems that appear to violate the theorists' expectations, at both the light and massive ends of the spectrum. An event they spotted on May 21, 2019, involved a black hole of an estimated 85 solar masses, right in the range where pair-instability supernovae should make such remnants impossible. And the following August 14, they detected a black hole swallowing an object weighing 2.6 suns, which is normally considered too massive for a neutron star but too light for a typical black hole.

Eventually the black hole detections will delineate a map of the universe in the way galaxy surveys currently do, says Rainer Weiss, an emeritus professor of physics at the Massachusetts Institute of Technology, who was the principal designer of LIGO. Once the numbers pile up, "we can actually begin to see the whole universe in black holes," he says. "Every piece of astrophysics will get something out of that."

To ramp up these observations, LIGO and Virgo have plans to improve their sensitivity, which will reveal not only more events but also more details about each merger. Among other things, physicists are eager to see the detailed "ringdown" waves that a post-merger black hole emanates as it settles into a spherical shape—an observation that could potentially reveal cracks in the general theory of relativity.

Having more observatories spread around the globe will also be crucial. KAGRA, a detector deep underground in Japan, has recently come online. Its location—and in particular its orientation with respect to incoming waves—will complement LIGO's and Virgo's and enable researchers to nail down the polarization of the gravitational waves, which encodes information about the orientation of the orbital plane and the spin of the spiraling objects. And India is planning to build another observatory, made in part with spare components from LIGO.

An even bigger trove of discoveries could come from observing neutron star mergers. The first such detection, called GW170817, seen in August 2017, was almost certainly the most intensely studied event in astronomy's history. And it solved a number of long-standing mysteries in one stroke, including the origin of gold and other heavy elements in the universe, as well as the cause of some gamma-ray bursts.

Further observations could allow scientists to explore the interiors of these objects. Neutron stars are thought to be as dense as matter can possibly be without collapsing into a black hole, but exactly how dense is anybody's guess. No laboratory experiment can study those conditions, and there are dozens of proposals for what happens there. Some theories predict that quarks—the subatomic components that make up protons and neutrons—should break free from one another and roam about, perhaps in superconducting, superfluid states. Others posit that heavier "strange" quarks form and become part of exotic cousins of the neutron.

Pinning down neutron star radii might allow physicists to evaluate the theories because they predict different "equations of state"—formulas that link pressure, temperature and density of matter. Such equations determine to what extent matter can be compressed and thus how wide or narrow a neutron star will be for a given mass and how massive such stars can get.

NIK SPENCER *Nature*

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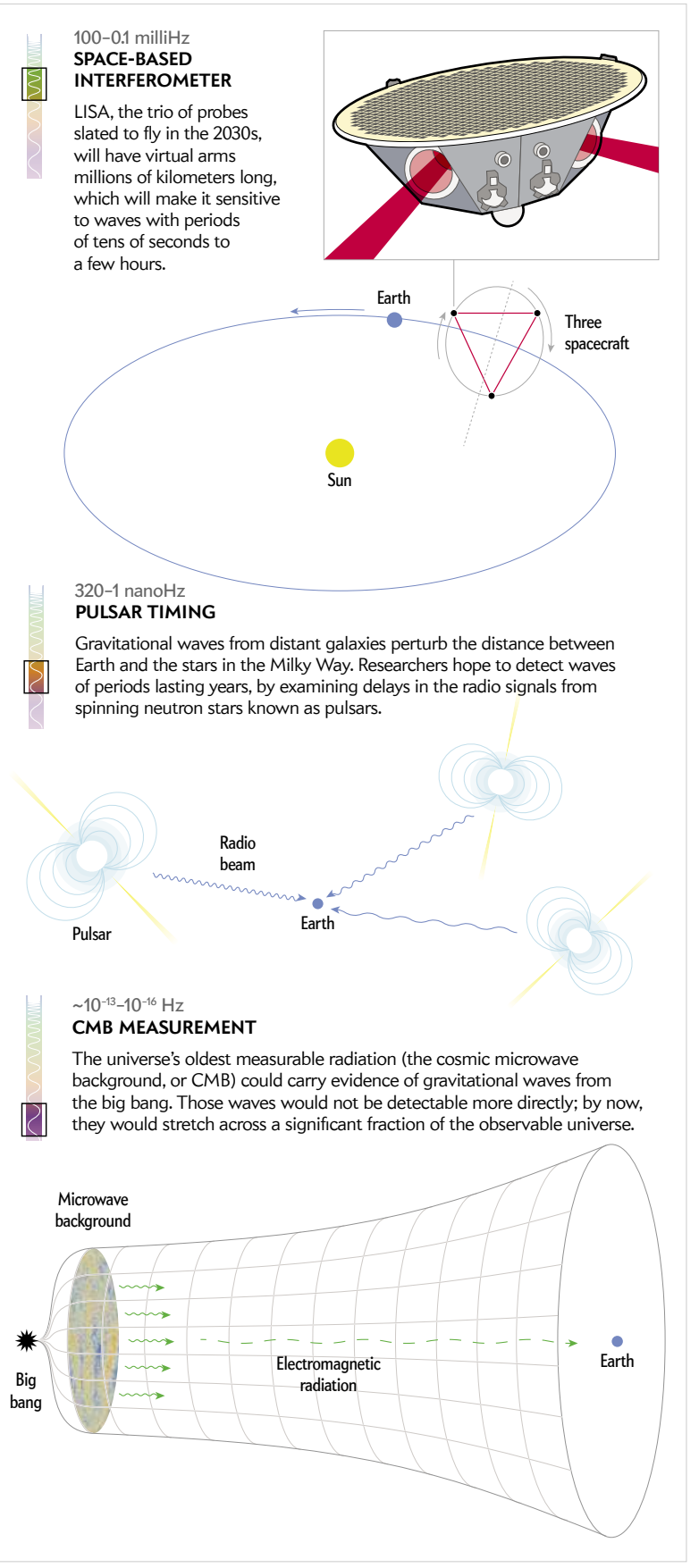
The 100-second-long signal in August 2017 eventually became too high in pitch for LIGO and Virgo to detect, which prevented the observatories from seeing the two neutron stars' final moments, when they should have deformed each other in ways that would have revealed their size and hardness or resistance to compression. Still, says Bangalore S. Sathyaprakash, a LIGO theoretical physicist at Pennsylvania State University, from that one event, "we can rule out equations of state that allow neutron star sizes larger than 15 kilometers in radius"—a figure that is consistent with other measurements and favors "softer" matter.

Future detections—and detectors—will give much more detail. Sathyaprakash says that the Einstein Telescope, a possible next-generation observatory dreamed up by a team in Europe, could take physicists far beyond an upper limit. "We want to be able to pin down the radius to the level of 100 meters," he says—a precision that would be astounding, given that these objects are millions of light-years away.

SIREN CALLS

SIGNALS SIMILAR to GW170817, which was observed through both gravitational waves and light, could have dramatic implications for cosmology. Schutz calculated in 1985 that the frequency, or pitch, of waves from spiraling objects, together with the rate at which that pitch increases, reveals information about the objects' collective mass. That determines how strong their waves should be at the source. By measuring the strength of the waves that reach Earth—the amplitude of the signal actually picked up by interferometers—one can then estimate the distance that the waves have traveled from the source. All other things being equal, a source that is twice as far, for example, will produce a signal half as strong. This type of signal has been dubbed a standard siren, in a nod to a common method of gauging distances in cosmology: stars called standard candles have a well-known brightness, which allows researchers to work out their distance from Earth.

By coupling the distance measurement of GW170817 with an estimate of how fast the galaxies in that region are receding from Earth, Schutz and his collaborators made a new and completely independent estimate of the Hubble constant—the universe's current rate of expansion. The result, part of a crop of papers released by LIGO, Virgo and some 70 other astronomy teams in October 2017, "ushers in a new era for both cosmology and astrophysics," says Wendy L. Freedman, an astronomer at the University of Chicago, who has made highly precise measurements of the Hubble con-


100–0.1 milliHz
SPACE-BASED INTERFEROMETER
LISA, the trio of probes slated to fly in the 2030s, will have virtual arms millions of kilometers long, which will make it sensitive to waves with periods of tens of seconds to a few hours.
Earth
Three spacecraft
Sun
320–1 nanoHz
PULSAR TIMING
Gravitational waves from distant galaxies perturb the distance between Earth and the stars in the Milky Way. Researchers hope to detect waves of periods lasting years, by examining delays in the radio signals from spinning neutron stars known as pulsars.
Radio beam
Pulsar
Earth
~10⁻¹³–10⁻¹⁶ Hz
CMB MEASUREMENT
The universe's oldest measurable radiation (the cosmic microwave background, or CMB) could carry evidence of gravitational waves from the big bang. Those waves would not be detectable more directly; by now, they would stretch across a significant fraction of the observable universe.
Microwave background
Big bang
Electromagnetic radiation
Earth

NIK SPENCER *Nature*

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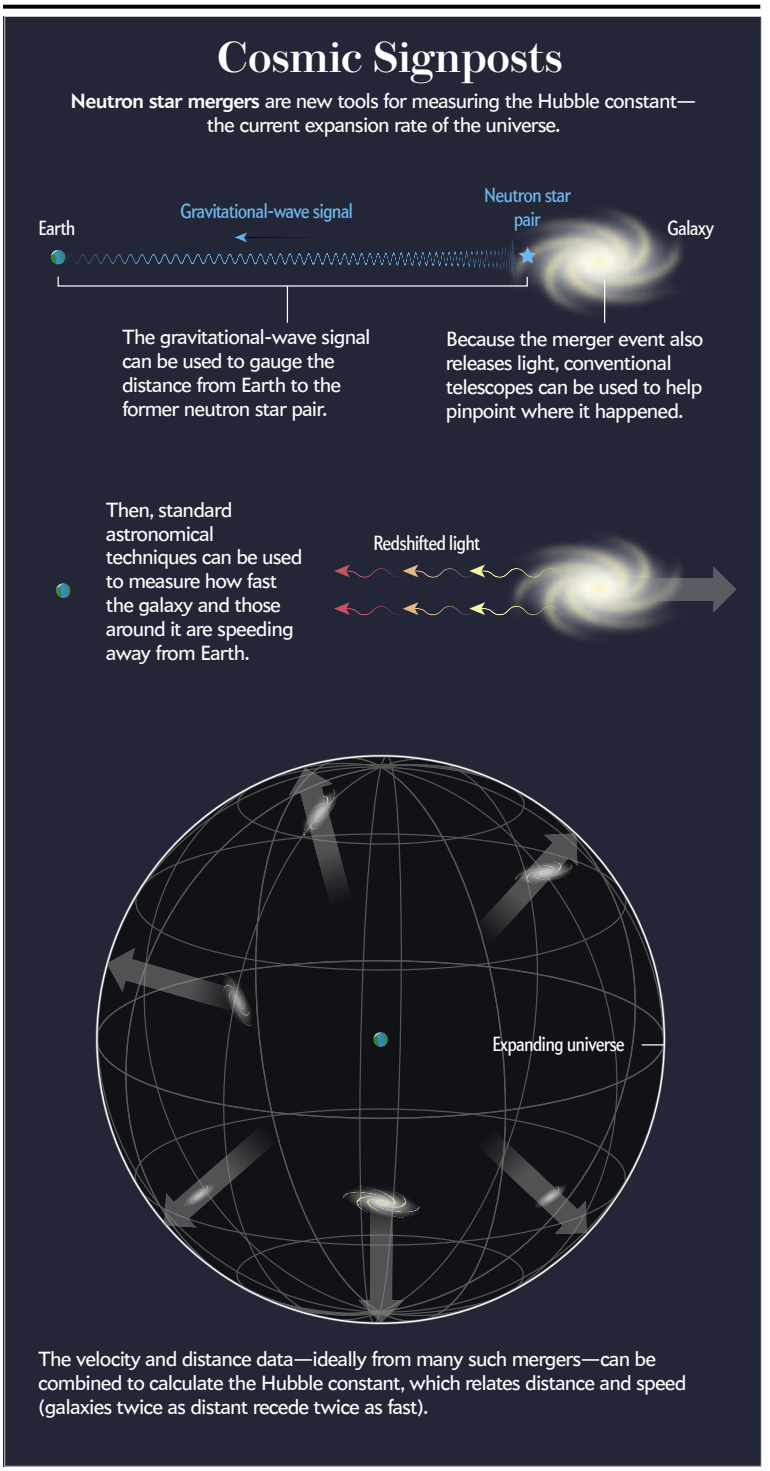
Cosmic Signposts
Neutron star mergers are new tools for measuring the Hubble constant—the current expansion rate of the universe.
Earth
Gravitational-wave signal
Neutron star pair
Galaxy
The gravitational-wave signal can be used to gauge the distance from Earth to the former neutron star pair.
Because the merger event also releases light, conventional telescopes can be used to help pinpoint where it happened.
Then, standard astronomical techniques can be used to measure how fast the galaxy and those around it are speeding away from Earth.
Redshifted light
Expanding universe
The velocity and distance data—ideally from many such mergers—can be combined to calculate the Hubble constant, which relates distance and speed (galaxies twice as distant recede twice as fast).

stant using time-honored but less direct techniques.

As a direct and independent measure of this constant, standard sirens could help to resolve a disagreement among cosmologists. State-of-the-art techniques, refined over nearly a century of work that started with Edwin Hubble himself, now give estimates that differ by a few percent. This first standard-siren measurement does not resolve the tension: the expansion rate it predicts falls somewhere in the middle of the range and, because it is based on just one merger event, has a large error bar. But in the future, researchers expect standard sirens to nail down the Hubble constant with an error of less than 1 percent. So far standard candles have done it with precisions of 2 to 3 percent.

Standard sirens could become even more powerful tools with space-based interferometers such as the Laser Interferometer Space Antenna (LISA), a trio of probes that the European Space Agency, which is leading the mission, plans to launch in the 2030s. LISA is designed to be sensitive to low-frequency waves that ground-based observatories cannot detect. This would give it access to more massive systems, which radiate stronger gravitational waves. In principle, LISA could pick up sirens from across the universe and, with the help of conventional telescopes, measure not just the current rate of cosmic expansion but also how that rate has evolved through the eons. Thus, LISA could help address cosmology's biggest puzzle: the nature of dark energy, the as yet unidentified cosmic component that is driving the universe's expansion to accelerate.

Whereas ground-based interferometers detect events that are brief and far between, LISA is expected to hear a cacophony of signals as soon as it turns on, including a constant chorus of tight binary white dwarfs—the ubiquitous remnants of sun-sized stars—in our own galaxy. "It's as if we lived in a noisy forest and we had to single out the sounds of individual birds," says astrophysicist Monica Colpi of the University of Milan–Bicocca in Italy, who is part of a committee setting the mission's science goals.

Occasionally LISA should see black hole mergers such as the ones LIGO does, but on a much grander scale. Most galaxies are thought to harbor a central supermassive black hole that weighs millions or even billions of solar masses. Over a scale of billions of years, galaxies might merge several times; eventually their central black holes might merge, too. These events are not frequent for individual galaxies, but because there are trillions of galaxies in the observable universe, a detectable merger should occur somewhere at least a few times per year. Scientists are also pursuing a separate way of detecting gravitational waves from pairs of these behemoths at earlier stages of their orbits. Using radio telescopes, they monitor pulsars inside the Milky Way and look for small variations in their signals caused by the passage of gravitational waves through the galaxy. Today there are three "pulsar-timing arrays," in Australia, Europe and North America, and a fourth is forming in China.

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Thanks to LISA's planned sensitivity and the strong signals produced by spiraling supermassive black holes, the observatory should be able to pick up gravitational waves from pairs of supermassive black holes months before they merge and see the merger in enough detail to test general relativity with high precision. After years of operation, LISA could accumulate enough distant events for researchers to reconstruct the hierarchical formation of galaxies—how small ones combined to form larger and larger ones—in the universe's history.

On the ground, too, physicists are beginning some "grand new ventures," Weiss says. A U.S. team envisions a Cosmic Explorer with 40-kilometer detecting arms—10 times as long as LIGO's—that would be sensitive to signals from events much farther away, perhaps across the entire observable universe.

The concept for the Einstein Telescope in Europe calls for a detector with 10-kilometer arms arranged in an equilateral triangle and placed in tunnels 100 meters or so underground. The quiet conditions there could help to broaden the observatory's reach to frequencies one tenth those detectable by current machines. That might allow scientists to find black holes beyond the range thought to be prohibited by pair-instability supernovae; at high enough masses, stars should have a different collapse mechanism and be able to form black holes of 100 solar masses or more.

If scientists are lucky, gravitational waves might even let them access the physics of the big bang itself at epochs that are not observable by any other means. In the first instants of the universe, two fundamental forces—the electromagnetic force and the weak nuclear force—were indistinguishable. When these forces separated, they might have produced gravitational waves that, today, could show up as a "random hiss" detectable by LISA, Schutz says. This hypothetical signal is distinct from a much longer-wavelength one from even earlier on, which might appear in the universe's oldest visible radiation: the cosmic microwave background. In 2014 a team reported that it had observed this effect with the BICEP2 telescope at the South Pole, but the researchers later acknowledged problems with that interpretation.

The next big discovery on Weiss's wish list is the signal from a collapsing star—something that astronomers might also observe as a type of supernova. But he has high hopes for what else might be on the horizon. "If we don't see something that we hadn't thought of," Weiss says, "I'd be disappointed." SA

Davide Castelvecchi is a senior reporter at *Nature* in London covering physics, astronomy, mathematics and computer science.

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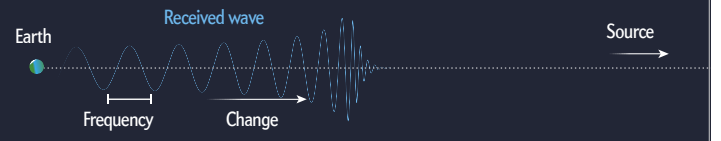
Making Waves

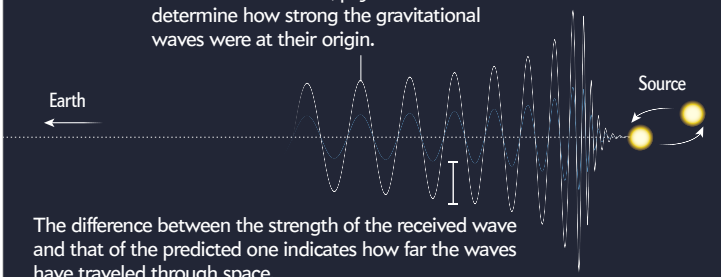
When two black holes or neutron stars spiral into each other, they produce distinctive ripples in spacetime called gravitational waves. Teams with LIGO's two detectors in the U.S. and with Virgo, the observatory's counterpart in Italy, have announced the detection of 50 events so far.

DECIPHERING A WAVE

When a signal is received, the frequency and rate of frequency change provide information about the masses of the objects in the binary source.



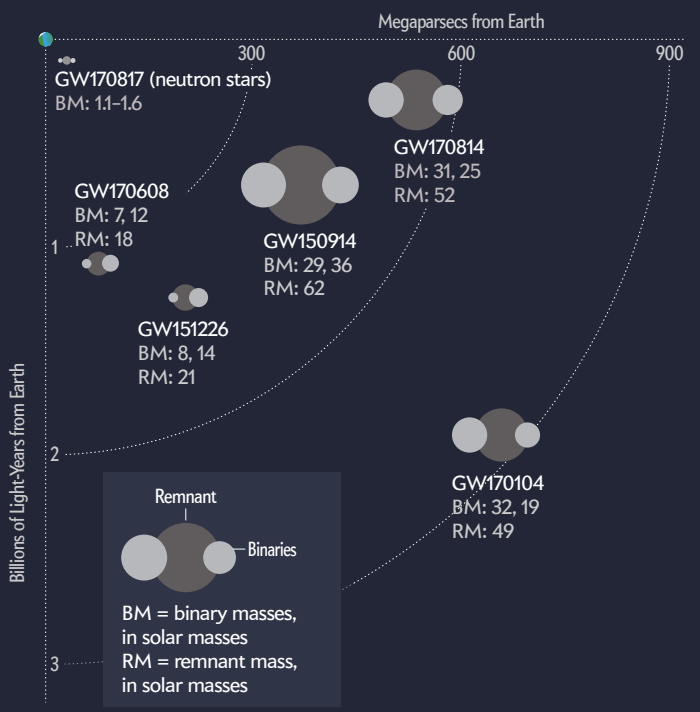
With this information, physicists can then determine how strong the gravitational waves were at their origin.



The difference between the strength of the received wave and that of the predicted one indicates how far the waves have traveled through space.

ALREADY DETECTED BY LIGO AND VIRGO

Here are seven of the binary mergers that the observatories have picked up so far. Each discovery was named with the date it was detected.



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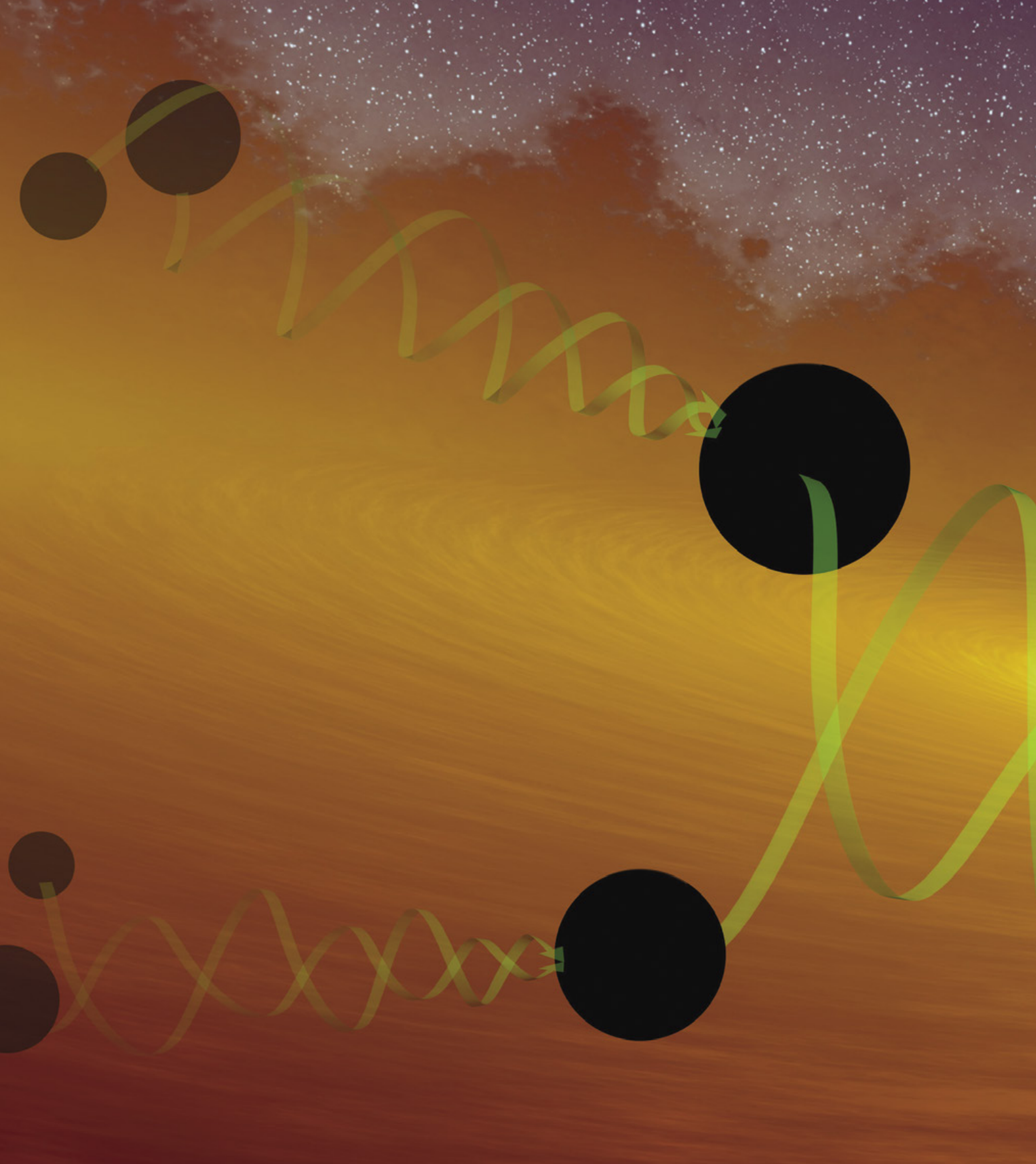

ARTIST'S CONCEPT illustrates a hierarchical scheme for the growth of black holes, showing how massive black holes can form from incremental mergers of smaller pairs. This scenario is thought to have spawned a merger, recently observed by LIGO and Virgo, that produced a black hole with a mass 142 times that of our sun.

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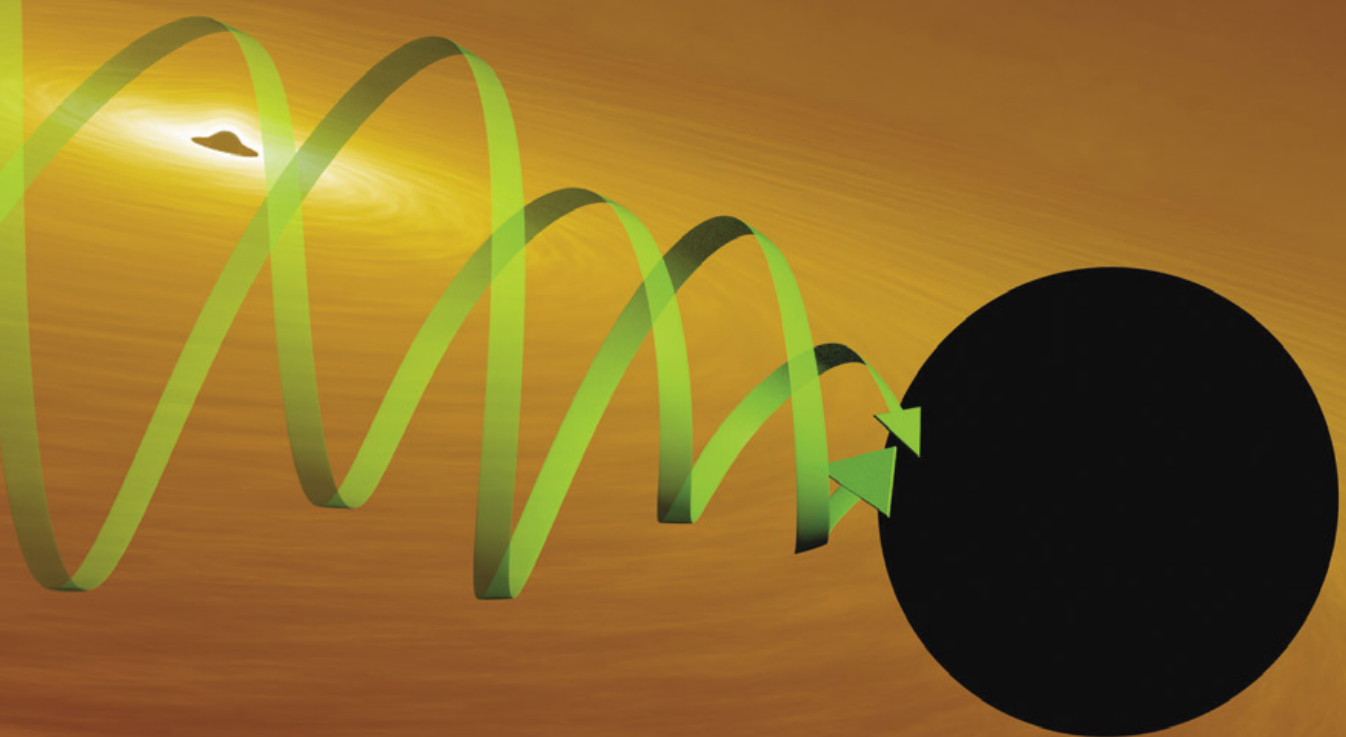
FIRST IN CLASS

LIGO and Virgo capture their most massive black holes yet, although astronomers are not sure how such heavyweights were created

By Adam Mann



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THE ALERT CAUGHT ZSUZSANNA MÁRKA'S ATTENTION immediately. Whenever the U.S.-based Laser Interferometer Gravitational-wave Observatory (LIGO) and its European counterpart Virgo detect a potential gravitational-wave event, an automatic notice is quickly dispatched to members of the collaboration.

Soon after receiving the notification for such an event on May 21, 2019, Márka, an astrophysicist at Columbia University, was on the team's internal Slack channel, sending an excited message to her husband, Szabolcs Márka, who also works with the LIGO group at Columbia, and to Imre Bartos of the University of Florida.

"This one was very special," Zsuzsanna Márka recalls. "I noticed [it involved] high masses right away."

Details from LIGO-Virgo's instruments indicated they had captured the signal of two behemoth black holes spinning around each other and merging into a single entity some 17 billion light-years away. The progenitor leviathans respectively weighed around 85 and 66 times the sun's mass, the heaviest pair detected to date by the facilities. And the subsequent black hole clocked in at an astounding 142 solar masses.

The breaking of records was not the only reason for the scientific elation. LIGO and Virgo, which use ultrasensitive quantum-mechanical sensors to identify ripples in the fabric of spacetime generated by cosmic cataclysms, had never before found black holes in what is known as the "intermediate" range between 100 and 1,000 solar masses. Astronomers have not previously seen an unambiguous example of such black holes—and are not even sure how they might be created.

But within the LIGO-Virgo data lay tantalizing clues to the environment in which these heavyweights formed, providing researchers with their best real-world observations of an object that had hitherto been largely theoretical. Those in the field know that the finding is a harbinger of things to come, and they are looking forward to soon having many more such signals to analyze.

"I see it as a threshold event—it's just the tip of the iceberg," says Priyamvada Natarajan, an astrophysicist at Yale University, who studies black hole formation but was not involved in the work. "I'm so stoked."

A black hole typically arises from the death of a massive star, which ends its life in a spectacular supernova explosion. As the star disintegrates, its dense core collapses into an object so compact and heavy that not even light can escape its gravitational pull—a black hole. The more massive the original star is, the more massive its subsequent remnant will be, at least until a certain point.

The death throes of extremely heavy stars, those greater than 130 times the sun's mass, include an extra twist. Temperatures get so hot in their core that photons of light begin generating pairs of electrons and their antiparticles, positrons. This change leads to a drop in the outward "radiation pressure" that the photons exert, causing the bulky outer layers to collapse inward with such ferocity that the entire core detonates in a thermonuclear explosion powerful enough to annihilate the star. No black hole relic can be left behind in that wake of stellar devastation, leading to a theoretical upper limit to black holes' size: around 65 solar masses.

The problem is that researchers know black holes with millions to billions of times the mass of the sun are lurking in the centers of pretty much every known large galaxy. So where exactly did these monsters come from?

Many stars form with a nearby stellar companion, and the two will orbit each other for their entire lives. If both of them are high-mass stars, they might explode at roughly the same time and leave behind a pair of black holes. These black holes can gravitationally attract and slowly spiral toward each other, and their eventual merger will send out copious gravitational waves traveling in all directions at the speed of light. LIGO-Virgo was built in part to capture such signals, and the collaboration's instruments have so far seen more than 10 such mergers, each involving black holes ranging from roughly five to 50 times the sun's mass.

PRECEDING PAGES: LIGO, CALTECH, M.I.T. AND R. HURT/IPAC

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But if two black holes can merge, then perhaps the resulting entity can find another black hole and repeat the process. "It's like a little assembly machine," Szabolcs Márka says. "You take a black hole and merge it, make a bigger black hole and merge it." Such so-called hierarchical mergers had been previously theorized but never seen.

Although the event in May 2019, which has been labeled GW190521, lit up LIGO-Virgo's sensors for less than a tenth of a second, it contained enticing information about the merging black hole pair. Specifically, the detectors found that each of the black holes was spinning around like an enormous top, a property that LIGO-Virgo had seen in only one black hole merger. This observation alone made GW190521's black holes unusual. But researchers were even more intrigued to see that their spins were not aligned—a telltale sign that the compact objects had not known each other for very long.

When two stars form two black holes, gravity acts as a harmonizing force, bringing each entity in line with its partner. The black holes should both spin in the same direction as their orbital path around each other, much like how the moon spins around its own axis in the same direction that it orbits Earth. The misaligned spins of GW190521's gigantic black holes hint that gravity did not have a great deal of time to work its coordinating magic before they merged. That idea suggests they did not originally form together but rather lived in an environment thick with other black holes.

"There is one special kind of place where this can happen," Bartos says. "And that's in the centers of galaxies, where smaller black holes tend to congregate in the vicinity of a supermassive black hole."

A lurking supermassive black hole makes a galactic center rather like the bottom of a well. Other heavy objects, such as stellar-mass black holes, will fall in the direction of its hefty attraction. Because GW190521 occurred so far away, it comes from a time when the universe was only half its current age, an era when many galaxies were blazing brightly as their central supermassive black holes were vigorously consuming gas and dust and belching out energy. Such swirling active galactic nuclei (AGNs), as they are known, would have been hotspots of commotion where smaller black holes could have met new partners and merged, explaining the new LIGO-Virgo event.

Such a picture is not guaranteed to be the situation with GW190521, but much of the evidence points in this direction. It is even possible that the heavier object in the pair, at 85 solar masses, formed from its own prior merger, Bartos says, although it cannot be ruled out that this extra-bulky black hole was created by some exotic, unknown process. "That's one of the beauties and difficulties of this field," he adds. "We are working with complex systems that are very far away." The team's findings appeared last September in two papers in *Physical Review Letters* and the *Astrophysical Journal Letters*.

Natarajan, who has been working on models to form black holes between 100 and a million times the sun's mass, says that the results are exciting because "they directly give you the stepping-stone to supermassive black holes." Astronomers know that supermassive black holes must have gone through such a middle stage, she adds, but until now evidence of that period had been elusive.

LIGO-Virgo's facilities are currently closed because of the ongoing COVID-19 pandemic. Once the instruments come back online, however, researchers are eager to see whether they will find more events involving black holes in this intermediate mass range. The fact that it has taken this long to see these first results suggests that such mergers are somewhat rare, though not exceedingly so. Upgrades to the observatories should give scientists a clearer view of the moments leading up to the merging events, helping to determine whether they occurred in an AGN or some different environment.

"THERE IS ONE SPECIAL KIND OF PLACE WHERE THIS CAN HAPPEN. AND THAT'S IN THE CENTERS OF GALAXIES, WHERE SMALLER BLACK HOLES TEND TO CONGREGATE IN THE VICINITY OF A SUPERMASSIVE BLACK HOLE."
—IMRE BARTOS *UNIVERSITY OF FLORIDA*

Particularly helpful data could come from other telescopes that hunt for flashes of light whenever they get a LIGO-Virgo alert. Studying the optical, ultraviolet or infrared counterparts to gravitational-wave events gives astronomers multiple pathways to understanding their details. Just after the May 2019 detection, the Zwicky Transient Facility at the Palomar Observatory in California spotted an optical flicker in the vicinity of a distant AGN, but it remains unclear whether the two results are related.

Nevertheless, people in the field are happy to be at this turning point. Although GW190521 will go down in history as the first intermediate black hole definitively discovered, researchers are confident that they will soon have plenty of other examples to learn from.

"From this moment on, we have agents that are teaching us about something we couldn't reach in any other way," Szabolcs Márka says. "Before this event, it was all a dream. Now it has become a testable theory." SA

Adam Mann is a journalist specializing in astronomy and physics. His work has appeared in *National Geographic*, the *Wall Street Journal*, *Wired*, and elsewhere.

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Black Hole Factories

Gravitational-wave astronomers are probing the origins of abnormally massive black holes—and with them, the inner workings of their colossal galactic homes

By Charlie Wood

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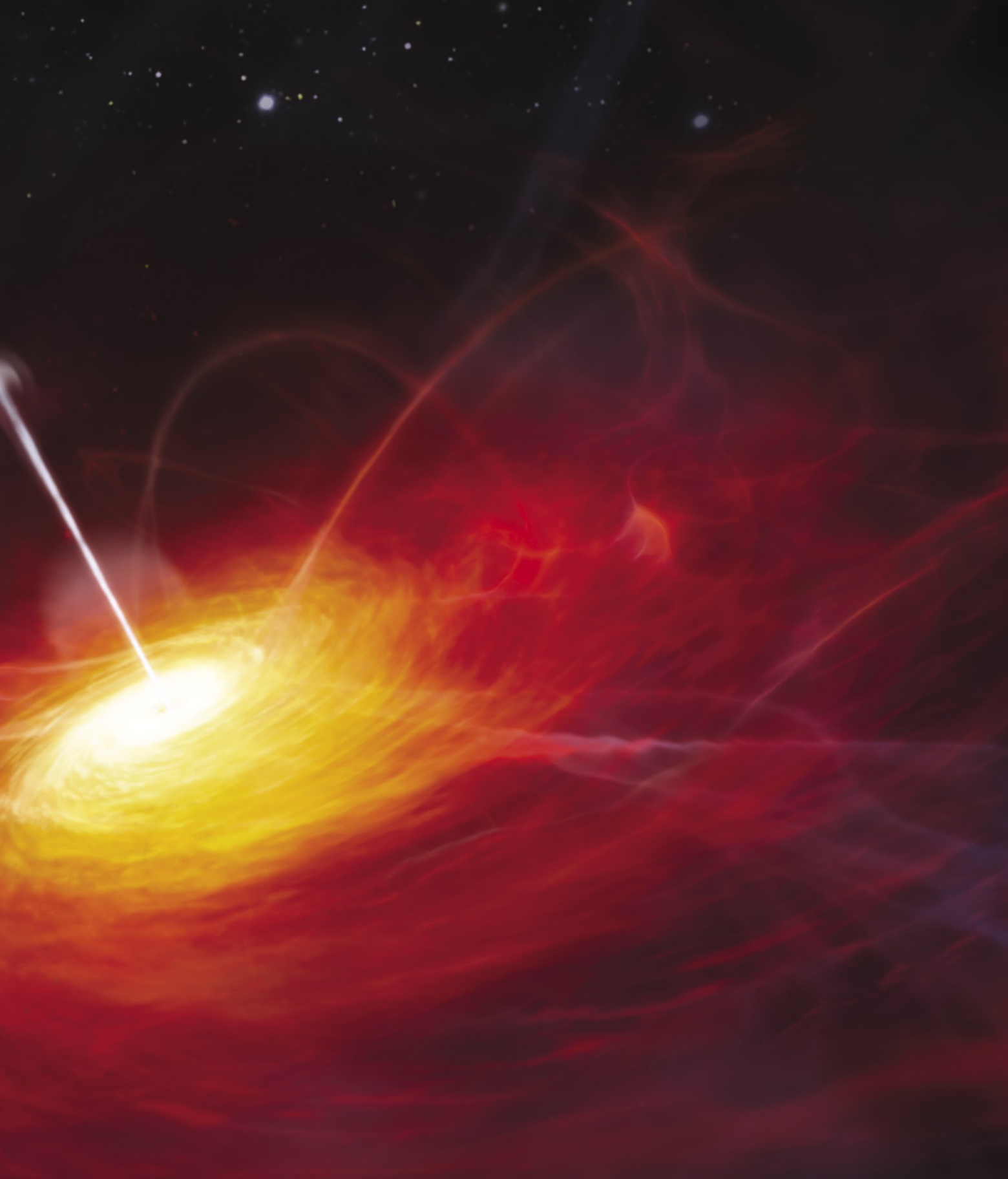

ARTIST'S IMPRESSION of an active galactic nucleus—a whirling disk of incandescent gas feeding a central supermassive black hole.

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IN 2015, WHEN SCIENTISTS, FOR THE FIRST TIME EVER, DIRECTLY DETECTED gravitational waves—ripples in spacetime—from colliding black holes, the result came as a shock to some astronomers. Based on previous studies of black holes using x-rays, many experts expected that each member of a merging pair would typically weigh about 10 times the sun's mass, but the 2015 merger featured twin giants three times that heavy. And the Laser Interferometer Gravitational-wave Observatory (LIGO), which enabled the discovery, has been spotting bizarrely big pairs ever since.

Black holes can certainly get supermassive—leviathans weighing billions of suns lurk at the hearts of most large galaxies. The question is: How could they grow so huge? Much of their bulk must be acquired after birth as they feast on gas and stars, but some theories suggest that mergers or chains of mergers may form a supermassive black hole's initial seed. Black hole matchmaking in the loneliness of space is not easy, though, so astrophysicists still puzzle over what circumstances could bring the objects together.

An emerging theory holds that LIGO's heavyweights arise near the cores of colossal galaxies, where violently incandescent disks of gas whirl around central supermassive black holes. Thanks to that omnipresent gas, these so-called active galactic nuclei (AGNs) could be factories for building big black holes out of smaller ones. If so, gravitational-wave detectors such as LIGO should be able to tease out signs of the hierarchical assembly of these swollen giants. Although the overall number of detections remains too low for conclusive classifications, some researchers have recently pointed to two hefty mergers as tantalizing hints of what AGN-facilitated black hole fusions might look like—a step toward using gravitational waves to study not only black holes but also the stars and galaxies that birthed them.

Figuring out how black hole pairs form "tells us a lot about stars," says Maya Fishbach, a LIGO member, who was not involved in the recent research. "Stars are the building blocks of galaxies. They're the atoms of astronomy."

Run-of-the-mill black holes, born from the remnants of an exploded star, would typically start off in orbits skewed against the plane of an AGN's disk of gas. Each time they would dip into that disk, however, friction would slow them and tip their paths in line with the disk. Once embedded, uneven pressures may shepherd those black holes from their initially scattered locations into special rings around the galaxy's central black hole—a trapping process analogous to the one that forms the seeds of planets in dusty disks around a single star but with black holes instead of microscopic piles of dust.

Imre Bartos, a LIGO collaboration member at the University of Florida, estimates that these galactic "migration traps" can quickly collect tens of thousands of black holes, many of which will get close enough to pair off. Then friction from the lingering gas would drive them to collide 1,000 times earlier than they otherwise would in empty space. "They will be forced to merge together," he says. It's like "a black hole assembly line, where we are adding black holes one after another."

Most of the universe's black hole mergers are thought to be one-off finales between stellar binaries—star couplets that were born, lived and died together—of moderate mass. But if AGN disks really are cranking out large black holes made from small ones, that population should eventually stand out in two ways from gravitational-wave observations.

Of the 10 black hole mergers confirmed by LIGO during its first two observing runs, nine seem to have come from pairs that spun slowly or not at all. A twirling crash—as would happen in an AGN disk—would, however, spin merging black holes up, typically causing subsequent generational mergers to spin even faster. Specifically, two black holes of even mass should spin at 70 percent of a theoretical top speed after colliding, so

PRECEDING PAGES: ESO AND M. KORNMESSER

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Bartos and his colleagues are on the lookout for collisions between already whirling dervishes.

They are also watching for mammoth mergers. Stars above a certain size are thought to undergo supernovae so savage that they blow their core to smithereens, preventing them from collapsing to form black holes. Theorists are unsure where the limit lies, but many expect the mass of stellar black holes to top out around that of 50 suns. "If you see a single event with 80 solar masses," says Davide Gerosa, an astrophysicist at the University of Birmingham in England, "that's a strong signature of some exotic formation channel." Black hole nurseries would be one explanation for heavy outliers.

Globular clusters, small clumps of stars within a galaxy, are another possible cosmic construction site for abnormally heavy, quickly spinning black holes. In these star-rich regions, black holes presumably could form dense crowds in which they would occasionally bump into one another. But recent research by Gerosa and one of his colleagues found that the recoil from such collisions would likely eject most pairs from the globular cluster, preventing them from finding future companions to merge with. Larger groups of stars, such as those within AGN disks, are more likely locations for strings of mergers, Gerosa says, because black holes there require much more recoil to escape.

BLACK HOLES CAN CERTAINLY GET SUPERMASSIVE—LEVIATHANS WEIGHING BILLIONS OF SUNS LURK AT THE HEARTS OF MOST LARGE GALAXIES. THE QUESTION IS: HOW COULD THEY GROW SO HUGE?

After years of theoretical speculation, some researchers are starting to see hints of an extra heavy population beginning to reveal itself. One of LIGO's heaviest catalogued mergers, GW170729, is exactly the kind an AGN disk would produce, Bartos and his colleagues proposed in *Physical Review Letters* in November 2019. In that event, one of the black holes weighed roughly 50 suns, and a measure of the pair's collective spin clocked them turning at about 40 percent of top speed before the merger—a hint that an earlier collision could have spun them up.

Another potential AGN-driven event was reported in October 2019, when researchers at the Institute for Advanced Study in Princeton, N.J., posted a preprint paper announcing two possible mergers from LIGO's data that, while not meeting LIGO's criteria for publication, may well be genuine. Called GW170817A and with a mass of roughly 56 suns and a combined premerger spin of 50 percent of the maximal value, this candidate merger matches predictions for an AGN collision even more closely than GW170729, according to a study published in the *Astrophysical Journal Letters* in February 2020. "This is exactly the same kind of event," Bartos says.

Neither occurrence is a smoking gun for an AGN black hole assembly line, however. GW170817A registered in only one of LIGO's two detectors—a potential sign that it was a false alarm arising from contaminating noise on Earth rather than some far-off celestial cataclysm. Moreover, because only a small fraction of the universe's stars reside in AGNs, Bartos's group concluded that the suggestive properties of these two mergers are just as likely to reflect normal binary black holes that just happened to be extra heavy and to spin extra fast as they are AGN black holes.

A much stronger candidate rattled gravitational-wave detectors on May 21, 2019. GW190521, calculations later revealed, was set off by a 66-solar-mass black hole crashing into a truly titanic 85-solar-mass black hole, both blowing past the theoretical 50-sun ceiling. What's more, the monstrous objects both spun at about 70 percent of the top theoretical speed—exactly how black holes resulting from chains of mergers should spin.

Other researchers agree that AGN disks could occasionally smack black holes together but stress that the community will need more data, as well as better predictions, to conclusively prove the reality of this rare collision type or others. "I don't think there's anyone who would be able to pick one side, because they'll know that if they're proven wrong, it will be in, like, a year," Fishbach says.

Regardless, the ability to distinguish one-off stellar binaries from AGN assembly lines and other putative production mechanisms for black hole mergers is coming. As LIGO's catalogue swells, categories based on spin and mass should become much clearer. Bartos suggests that traditional astronomy based on light rather than gravitational waves could help, too. Gravitational crashes that align in the sky with known AGNs will supply further hints. And if astronomers can use their telescopes to rapidly observe gravitational-wave sources with AGN signatures as they are detected, a recent publication in the *Astrophysical Journal Letters* proposes, they may glimpse flashes of light hypothesized to come from postcollision shock waves in the gas. Indeed, the May 2019 merger coincided with a flare captured by astronomers at the Zwicky Transient Facility in California—one more tantalizing hint that Bartos and his colleagues are on the right track.

In the midst of building this new black hole taxonomy, astrophysicists are already brainstorming what they will be able to do with it. Light reveals what a galaxy is made of, says Katelyn Breivik, an astrophysicist at the Flatiron Institute's Center for Computational Astrophysics in New York City, but gravitational waves may unmask its more subtle dynamics. "If you have black holes that are embedded in these disks," she says, "they are like literal gravitational probes into the shape of these disks," revealing mass and motion.

While those probes may have yet to fully materialize, LIGO's big, spinning black holes encourage Bartos that they are not far off. "I was used to predicting the far future," he says. "Coming from there to having these black holes that basically reproduce what you're predicting is super exciting." SA

Charlie Wood is a journalist covering discoveries in the physical sciences both on and off the planet. His writing has appeared in *Quanta Magazine*, *Popular Science*, and elsewhere.

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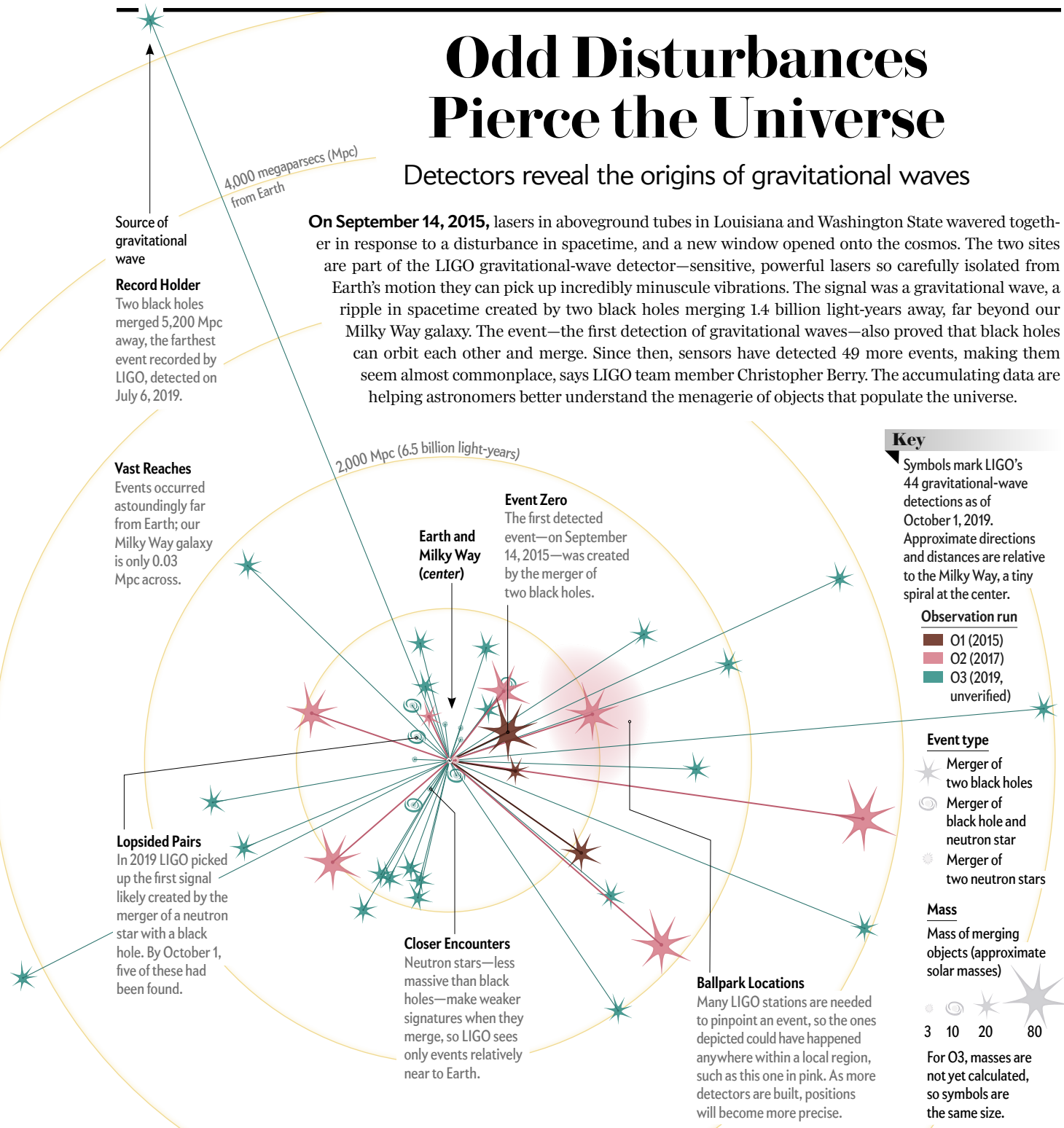
Text and Graphic by Katie Peek

Odd Disturbances Pierce the Universe

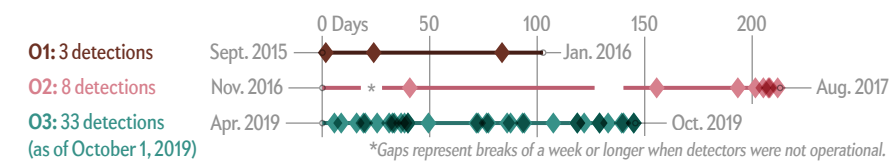
Detectors reveal the origins of gravitational waves

On September 14, 2015, lasers in aboveground tubes in Louisiana and Washington State wavered together in response to a disturbance in spacetime, and a new window opened onto the cosmos. The two sites are part of the LIGO gravitational-wave detector—sensitive, powerful lasers so carefully isolated from Earth's motion they can pick up incredibly minuscule vibrations. The signal was a gravitational wave, a ripple in spacetime created by two black holes merging 1.4 billion light-years away, far beyond our Milky Way galaxy. The event—the first detection of gravitational waves—also proved that black holes can orbit each other and merge. Since then, sensors have detected 49 more events, making them seem almost commonplace, says LIGO team member Christopher Berry. The accumulating data are helping astronomers better understand the menagerie of objects that populate the universe.


4,000 megaparsecs (Mpc) from Earth
Source of gravitational wave
Record Holder
Two black holes merged 5,200 Mpc away, the farthest event recorded by LIGO, detected on July 6, 2019.
2,000 Mpc (6.5 billion light-years)
Vast Reaches
Events occurred astoundingly far from Earth; our Milky Way galaxy is only 0.03 Mpc across.
Earth and Milky Way (center)
Event Zero
The first detected event—on September 14, 2015—was created by the merger of two black holes.
Lopsided Pairs
In 2019 LIGO picked up the first signal likely created by the merger of a neutron star with a black hole. By October 1, five of these had been found.
Closer Encounters
Neutron stars—less massive than black holes—make weaker signatures when they merge, so LIGO sees only events relatively near to Earth.
Ballpark Locations
Many LIGO stations are needed to pinpoint an event, so the ones depicted could have happened anywhere within a local region, such as this one in pink. As more detectors are built, positions will become more precise.
Key
Symbols mark LIGO's 44 gravitational-wave detections as of October 1, 2019. Approximate directions and distances are relative to the Milky Way, a tiny spiral at the center.
Observation run
O1 (2015)
O2 (2017)
O3 (2019, unverified)
Event type
Merger of two black holes
Merger of black hole and neutron star
Merger of two neutron stars
Mass
Mass of merging objects (approximate solar masses)
3
10
20
80
For O3, masses are not yet calculated, so symbols are the same size.

Quickening Pace of Discovery

LIGO detected three confirmed events during its first run—dubbed "O1"—over four months in 2015. By run O3, detections were piling up five times as fast (although some may not withstand scientific scrutiny). Improvements in LIGO's physical setup have led to the increase.



SOURCES: GRACEDB—LIGO GRAVITATIONAL-WAVE CANDIDATE EVENT DATABASE; "GWTC-1: A GRAVITATIONAL-WAVE TRANSIENT CATALOG OF COMPACT BINARY MERGERS OBSERVED BY LIGO AND VIRGO DURING THE FIRST AND SECOND OBSERVING RUNS," BY B. P. ABBOTT ET AL. (LIGO SCIENTIFIC COLLABORATION AND VIRGO COLLABORATION). IN *PHYSICAL REVIEW X*, VOL. 9, ARTICLE 031040; JULY 2019

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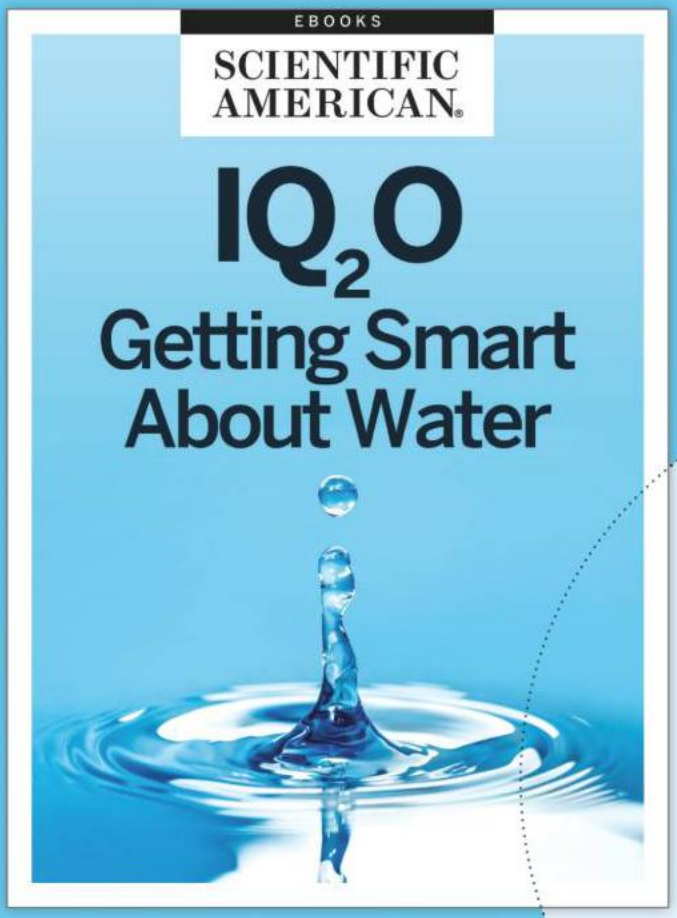

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